A PRELIMINARY SYSTEM DYNAMICS MODEL OF A CONSTRUCTED WETLAND FOR THE MITIGATION OF METALS IN USAF STORM WATER

THESIS

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AFIT/GEE/ENV/94S-24

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The views expressed in this thesis are those of the author and do not reflect the official policy of the Department of Defense or the U.S. Government.

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THESIS

Presented to the faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Engineering and Environmental Management

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September 1994

Preface

This thesis would not have been possible without the assistance and support of people both inside and outside the Air Force Institute of Technology (AFIT). I would like to thank Lt Colonel Mike Shelley for helping me to focus the content and scope of this thesis research. Lt Colonel Shelley's classes and thesis sessions were both challenging and productive. I am also very grateful to the assistance provided by Major Andy Howell who took it upon himself to teach the modeling concepts needed to complete this project.

I would like to thank Dr Jim Amon of Wright State University for sparking my interest in wetlands and providing two up-close and personal tours of the Beaver Creek Wetlands. I would also like to thank Mr Bob Ellis and the environmental staff at Warner Robins AFB who provided both information and time away from their busy schedules to accommodate my visit to their wetland areas.

Thanks also goes to my family and my family to be. My parents who have always been willing to listen and support me were once again always just a telephone call away whenever I needed to talk. Most importantly however, has been the time I have spent with my fiancée, and soon to be my wife, Amy Woitas. She has helped me realize what is really important in my life, and I cannot imagine how I would have accomplished this project without her. I am truly looking forward to starting a family with Amy as my wife.

Most of all, I must give God the glory for the work that was accomplished over the past fifteen months. His words from the Apostle Paul to the Christians at Phillipi have been my guiding light, "I can do all things through Christ who gives me strength" (Phillipians 4:13).

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Abstract

This thesis determines the potential removal and corresponding accumulation of trace metals from Air Force storm water in a constructed wetland through the use of a System Dynamics model. The goal is to determine whether constructed wetlands used as storm water best management practices provide efficient metal removal while creating only benign accumulations of such pollutants. Its purpose is to allow Base Civil Engineers and Environmental Managers a better tool to assess the long-term effects of a constructed wetland used as a storm water mitigation technique. The research is limited to the assessment of typical metal concentrations found in Air Force storm water and a hypothetical constructed wetland system.

The thesis uses reviews of present literature to examine the sediment and metal removal processes found in constructed wetlands as well as the hydrologic and biologic functions which affect these processes. These processes are mathematically described and attached to five different sectors which together simulate a constructed wetland as a whole. Constant storm water flows and concentrations typical of Air Force runoff are used to evaluate the metal mitigation potential of such best management practices.

The recommendation resulting from this research is that the Air Force should be able to consider constructed wetlands as a viable best management practice to mitigate metals in storm water. This best management practice can offer a high metal removal efficiency if properly sized, however inefficient removal can be expected in systems with detention times of less than five days. The Air Force's long-term use of properly designed constructed wetlands as storm water best management practices should not prove to accumulate metal concentrations of regulatory concern.

A PRELIMINARY SYSTEM DYNAMICS MODEL OF A CONSTRUCTED WETLAND FOR THE MITIGATION OF METALS IN USAF STORM WATER

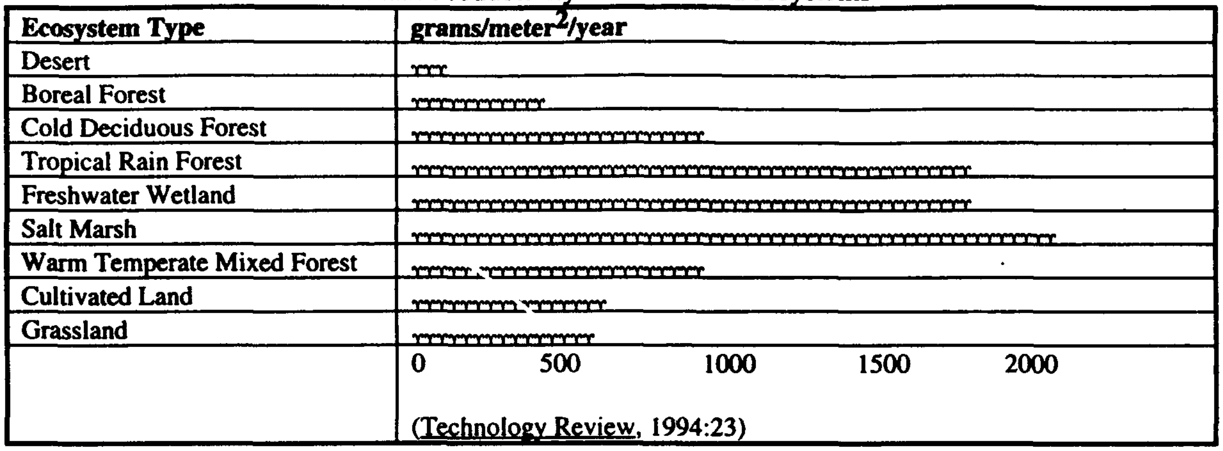
I. Introduction

Non-point source pollution, often referred to generally as storm water, has come under increasing scrutiny over the past decade, as more and more point sources have been found and successfully regulated. Federal Laws such as the Clean Water Act have made great strides in regulating and hence limiting generators of point source water pollution. Environmental Protection Agency focus has recently turned from this past direction to that of non-point source pollution, and for good reason. EPA studies have concluded that non-point source pollution is generally more serious than those from point sources. The health risks were nearly equal, but the ecological risks posed were "identified as a more serious problem" (GAO, 1990:50) This changed focus has permeated all phases of industry, construction, agricultural, and urban activities with special emphasis on those urban areas which contain vast pavements such as highways and airfields. Not an island unto itself, Air Force facilities, which typically include large open pavements and operations which create copious amounts of storm water runoff and associated pollutants, have become of increasing concern to both State and Federal Regulators. EPA and State regulators are currently developing storm water rules and requirements similar to those already contained in current National Pollutant Discharge Elimination System permits regulating Air Force point source discharges. As regulators continue to pursue storm water rule making, AF Installations are concurrently determining which best management practices (BMPs) will allow their installations to meet these new requirements. Most, if not all current BMPs were thoroughly described by Capt. Pete Ridilla and Lt. Brad Hoagland along with an in-depth discussion of general storm water regulations and historical background in their thesis entitled "Analysis of Best Management Practices for

Storm Water Compliance at Air Force Airfields." One such BMP discussed in their thesis was the use of CWs for mitigation of storm water pollution. In fact, the sample problem included in Appendix B (pages 69-73) steps the reader through numerous tables in determining the most applicable BMP (a CW) for a particular storm water pollutant discharge (Hoagland, 1993:69-73). The selection of a CW for mitigation of storm water effects is not a new answer. CWs have found increasing popularity as treatment systems for a variety of water-born pollutants in the past decade. However, long term effects of using such treatment systems for storm water mitigation have not been fully documented, since expected lifetimes of such systems are not yet well quantified.

Wetlands have always acted as purifiers of both naturally occurring and anthropogenic water pollutants. However, only within the past few decades has their purification function been realized and sought out as a beneficial resource. Swamps, marshes, and bogs have been long time settings for murder mysteries and science fiction horror movies, and have been generally thought of as homes for mosquitoes, crocodiles, and other unsavory animal fare. In actuality, wetlands do provide homes for such animals, but for many others also, along with diverse and rich plant and microbial communities. According to a recent article in Scientific American, wetlands are ecologically rich; they are often as diverse as rain forests (Kusler, 1994:64). This fact is confirmed by Thompson and Yocom and graphically presented below as a comparison of biomass productivity of both fresh and saltwater marshlands with other such ecosystems (Thompson, 1993:23).

Table 1.1
Plant Productivity of Different Ecosystems



The Scientific American article continues with the benefits provided by wetlands as limiting the damaging effects of waves, conveying and storing floodwaters, trapping sediment and reducing pollution--this last attribute has earned them the sobriquet "nature's kidneys" (Kusler, 1994:64). Little past interest in these bountiful ecosystems has led to little research about their function and ancillary benefits and a general fear and disgust of living near them. Many of the naturally occurring wetlands across the US have been filled in and plowed or paved for more financially lucrative activities. Roughly half the nation's wetlands endowment has been destroyed since colonial times. States such as California, Iowa, and Ohio retain only 10 percent of their original wetland expanses (Hammond, 1991:138). These losses continue to happen in light of Section 404 of the Clean Water Act of 1972. This provision regulates the discharge of dredged or fill material into "the waters of the United States," and thus affects a wide array of construction activities in a range of aquatic habitats. This section of the law seems to be used as a bargaining tool and easily circumvented due to its vague wording. The Clean Water Act is expected to be reauthorized in the near future which means Section 404 will probably be revisited and redefined. More intense scrutiny of these ecosystems can only help their cause and seems bound to happen under the current administration. This

additional investigation should greatly help scientists to further understand the functions and assets of these diverse ecosystems.

Although very little of the world has realized the benefits wetland ecosystems provide, many individual groups have researched and created pilot to full scale CW treatment systems for almost every type of water pollution imaginable. The following data lists historic "firsts" in use of CWs to treat a variety of waste waters (Morishi/Bastian, 1993:60):

1956--livestock wastewaters--experimental; Seidel
1975--petroleum refinery wastewaters--operational; Litchfield
1978--textile mill wastewaters--operational; Kickuth
1978--acid mine drainage--experimental; Huntsman
1979--fish rearing pond discharge--operational; Hammer and Rodgers
1982--acid mine drainage--operational; Pesavento
1982--reduction of lake eutrophication--experimental; Reddy
1982--urban storm water runoff--operational; Silverman
1983--pulp/paper mill wastewaters--experimental; Thut
1985--photochemical laboratory wastewaters--experimental; Wolverton
1985--seafood processing wastewater--experimental; Guida and Kugelman
1988--compost leachate--operational; Pauly
1988--landfill leachate--experimental; Trautman and Porter
1988--livestock wastewaters--operational; Hammer and Pullin
1989--sugar beet processing plant wastewaters; Anderson
1989--reduction of lake eutrophication--operational; Szilagyi
1990--harbor dredged materials--experimental; Pauly
1991--pulp/paper mill wastewaters--operational; Thut

As one can easily see, CWs have been developed to treat many different waste water sources, however CWs should not be viewed as a universal treatment for all waste waters. Studies have primarily focused on CW treatment systems for sanitary water pollution, with limited data available on systems developed for other pollutant streams including storm water runoff. Storm water pollutants tend to be much more diverse and variable than normal sanitary water pollutants which are typically constant or at least highly predictable. CW systems have been developed in both temperate and cold regions with mixed results due to great variations in site conditions.

Since untreated waste waters cannot be legally dumped into naturally occurring wetlands or any other naturally occurring water source, CWs are one way of getting the best of both worlds. CWs are most often regulated in the same manner as other waste water treatment systems, much like a trickling filter or activated sludge processes. These systems utilize passive filtration, sedimentation, and microbial actions that are universally available in most wetlands which require little energy and maintenance. They also provide natural habitats for animal species of all kinds (Olson, 1991:32). Although CWs rarely, if ever reach the level of plant and animal diversification normally found in naturally occurring wetlands, the habitat they do provide is often a very important one.

CWs do seem to offer an enormous potential for storm water treatment, however everything that seems too good to be true usually is. Such may be the case with the use of CW's to mitigate AF storm water. One potential problem with such treatment systems is the fact that they receive such a variety of pollutants. Many of these incoming pollutants are indeed degraded and their toxicity reduced. CW treatment of pollutants such as phosphorous, nitrogen, and biochemical oxygen demand (BOD) have been well documented. Even petroleum wastes have been effectively degraded to non-toxic constituents within a CW. Other pollutants however, such as trace metals, are by far less degradable and have a high affinity for accumulation in the CW itself. This accumulation of trace metals within the wetland can have potentially toxic effects on plant, animal, and microbial communities in and around the CW. Furthermore, the possibility of reduced removal efficiency and potential creation of a hazardous waste site must be thoroughly evaluated prior to the selection of such a storm water mitigation technique. In order to better determine if a CW is in fact capable of dealing with the trace metal concentrations inherent in AF storm water and not accumulating toxic levels for later remediation and disposal at great cost to the AF, this paper will attempt to describe and model the effects of a CW receiving typical AF storm water. The resulting data should point out if such a

BMP is actually applicable to AF storm water runoff, and if so, what design and maintenance techniques might be employed to mitigate the possibility of trace metal accumulation and potential toxicity.

One problem encountered by Capt. Ridilla and Lt. Hoagland in their thesis was the gathering of actual storm water pollution data from AF installations which was not widely available at the time of their writing. Few AF bases' storm water had been sampled although installations had been selected by their appropriate headquarters to provide such information as a requirement under the AF Storm Water Group Application. Limited data is currently now available and was used as an input for this wetland modeling effort.

Specific Problem

The purpose of this research is to analyze, model, and provide general design and maintenance considerations for a CW as a best management practice in controlling and mitigating the effects of trace metals in storm water runoff from a typical AF installation. This information is provided to assist Base Civil Engineers and Environmental Managers in deciding whether a CW is applicable to their specific situation.

Investigative Questions

The associated investigative questions are as follows:

1. Which trace metals and respective concentrations can be found in storm water produced at a typical AF installation?
2. What processes does a CW perform to remove metal concentrations in storm water and where do metals accumulate to create potentially toxic conditions in the CW?

3. Can these processes be effectively represented in a model to predict metal accumulation locations and concentrations of varying storm water inputs and CW sizes?
4. What design and maintenance procedures will help AF base level managers create and operate a CW as a storm water BMP to effectively mitigate trace metals while minimizing the toxicity of trace metal accumulation?

Scope and Limitations

This research examines the processes and design characteristics of CW as a BMP for mitigation of trace metals in AF storm water. The resulting information is intended to provide the reader a general background of CW trace metal removal functions based on typical AF storm water loadings. AF installations, however may or may not be "typical" in their actual storm water quantities and qualities, and modifications and further site specific research may be needed.

CWs are applicable in many different applications and climates, however not all of these differences are covered here, nor could they possibly be covered in a single text. Each CW must be created specifically for an individual application, with considerations made for climate, water table, plant species, etc. These considerations and techniques are discussed generally, however additional guidance should be sought for site specific guidance on these topics.

AF installations are found world wide and come under the jurisdiction of both federal, state, and local regulations. Many states have specific guidance on the creation of CWs and their use in waste water treatment. Prior to starting any such project it is highly encouraged that each AF installation contact all interested parties before any designs are considered. State and federal regulators may be able to provide site specific guidance and informative area case study information about other such systems already in operation.

II. Literature Review

This chapter provides a description of the literature concerning the application of CWs for the purpose of reducing AF storm water pollutants with particular emphasis on potential problems associated with trace metal accumulation. The general characteristics of Air Force storm water are discussed first, with brief reference to anticipated Federal storm water regulatory direction. The populations, processes, and efficiencies involved in storm water pollutant removal, including trace metal removal, within a typical CW are discussed next, followed by a discussion of potential problems associated with trace metal accumulation. A general discussion follows, on how CW processes might be simulated using a computer based model to predict long-term effects. Finally, CW design procedures and considerations are reviewed based on their application to storm water mitigation while optimizing trace metal removal in AF storm water.

Storm Water Characteristics

Sources - Storm water originates from almost every area on an AF installation, however sources contributing to trace metal concentrations typically are found in water runoff from large paved areas with industrial operations such as aircraft parking ramps, runways, taxiways, and maintenance areas. Capt. Ridilla and Lt. Hoagland thesis lists specific problem areas associated with storm water pollutant generation from aircraft/maintenance sources on typical AF installations. The following list is adapted from their work:

- Aircraft and ground vehicle washing and cleaning
- Fueling operations
- Aircraft maintenance and repair work
- Engine test cell operations
- De/anti-icing operations of aircraft and pavements
- Ground vehicle maintenance

Other areas of concern might be vehicle parking lots such as the BX and Commissary or heavily traveled streets. Such results were quantified by Sartor and Boyd in 1972. The following table lists their findings of trace metal concentrations in street debris:

Table 2.1
Concentrations (µg metal/g dry solids) of Copper, Zinc, Lead, and Cadmium in Dry Street Surface Debris

Metal	Concentration
Copper	104 - 200
Zinc	370 - 760
Lead	530 - 1810
Cadmium	2.4 - 3.4

SSD (Maryland), 1991:32

Other sources of storm water generation may not provide the same quantities of trace metal pollutant concentrations as airfield operations or vehicle traffic areas, however a full evaluation of base activities should be able to determine exact locations and specific concentrations of trace metals that may be creating storm water associated hazards. Many AF installations have already determined or are preparing to determine possible storm water pollutant sources through contractor performed surveys. Such surveys can greatly reduce the chance of any hazardous pollutants entering storm water runoff. As numerous authors, including Capt. Ridilla and Lt. Hoagland in their thesis stress, pollution prevention is the key to successful storm water mitigation including trace metal pollutant reduction. If pollutants can be prevented from entering an installation's storm water, few if any, best management practices will need to be evaluated and funded (Hoagland, 1993:17, Olson, 1991:12-13).

Although prevention is the key to storm water mitigation and the trace metals inherent in those volumes, many pollutants may be impossible or unfeasible to stop at their source, so other measures need to be implemented. To understand the possible problems associated with trace metal accumulation and potential toxicity in a CW, one

must first understand the trace metal characteristics of typical storm water and the corresponding concentrations of such pollutants associated with typical AF storm water.

Unlike rural storm water and non point pollution, urban storm water is typically collected and concentrated in a storm sewer system which may or may not receive treatment prior to discharge into a receiving water body. AF installations have such storm sewer systems, which have generally bypassed any type of treatment facilities due to their shock-type loading and cost of implementation. This collection and concentration of storm water should allow each installation to design specific treatment systems for this type of waste water which may or may not require primary waste water treatment facilities.

Typical Storm Water Concentrations - According to Metcalf and Eddy, typical storm water pollutant concentrations differ from those of rainfall and municipal waste water. Their findings are listed in the following table (Metcalf & Eddy, 1991:1120):

Table 2.2

Comparison of Characteristics of Combined Wastewater and Other Sources

Parameter	Unit	Rainfall	Storm water Runoff	Municipal Waste Water
Suspended Solids	mg/L		67-101	100-350
BOD_5	mg/L	1-13	8-10	110-400
COD	mg/L	9-16	40-73	250-1000
Fecal coliform bacteria	MPN/100 ml		1000-21,000	10^6-10^7
Nitrogen (total as N)	mg/L			20-85
TKN			0.43-1.0	20-85
Nitrate		0.05-1.0	0.48-0.91	0
Phosphorus (total as P)	mg/L	0.02-0.15	0.67-1.66	4-15
Metals	µg/L			
Copper			27-33	
Lead		30-70	30-144	
Zinc			135-226	

Although the storm water values above are not typically as high as the municipal waste water values, it is of interest to note that storm water has a wider range of pollutants than does municipal sewage, including trace metal concentrations which are noticeably absent from the municipal sewage. This greater variety of pollutants tends to create problems for conventional waste water treatment systems which have been designed to treat large constant flows of water containing relatively constant concentrations of pollutants. In contrast to a constant pollutant loading, storm water pollutants are usually concentrated in the first part of the storm flow and greatly decrease as the precipitation event continues. This large, sudden flow of pollutants characteristic of storm water flows has been labeled a "first flush effect" (Morishi/Taylor, 1993:141; Hammer/Livingston, 1990:254; Di Toro, 1979:50). Such concentrations of specific pollutants can create intolerable situations in conventional waste water treatment systems killing microbial populations associated with both aerobic and anaerobic systems, greatly reducing the efficiency of such systems. Such scenarios of sudden large water flows and pollutant concentrations have led to the bypass of storm water around sewage treatment facilities directly discharging into receiving waters. Richard Field, in his article entitled "Urban Runoff: Pollution Sources, Control, and Treatment", relates just this problem. He states that, "Due to adverse and intense flow conditions and unpredictable shock loading effects, it has been difficult to adapt existing treatment methods to storm-generated overflows, especially the microorganism-dependent biological processes (Field, 1985:202)."

The effects of trace metals concentrations in receiving waters were highlighted by the Nationwide Urban Runoff Program results from 1978-1983. This study investigated the effects of urban runoff on receiving waters and the respective water quality problems. One of the NURP's principal conclusions was that heavy metals are the most prevalent

priority pollutant with concentrations far exceeding EPA ambient water quality standards. The following table contains some of the results of this study (SSD, 1991:30):

Table 2.3

Metals Studied During the NURP Project, the Frequencies of Detection (%), and the Ranges of Concentrations (μg/l) in the Samples

Metal	Frequency of detection (%)	Range of concentration (μg/l)
Antimony	14	6 - 23
Arsenic	58	1 - 50
Beryllium	17	1 - 49
Cadmium	55	0.1 - 14
Chromium	57	1 - 34
Copper	96	1 - 100
Lead	96	6 - 460
Mercury	16	0.5 - 1.2
Nickel	48	1 - 182
Selenium	19	2 - 77
Silver	12	0.2 - 0.8
Thallium	10	1 - 14
Zinc	95	10 - 2400

AF Storm Water Concentrations - Eleven different AF bases were selected to provide representative storm water samples in 1992 under Part 2 of the EPA's Group Application requirements. These bases included a wide variety of climates, mission elements, and general runoff characteristics. This variety of storm water inputs was intended to provide information concerning the AF storm water group application that was to be issued by the EPA and states (those having NPDES authority) covering the majority of AF bases in the United States. The Federal Register dated 19 November 1993 provided notice for draft National Pollutant Discharge Elimination System (NPDES) general permits and accompanying fact sheets for storm water discharges associated with industrial activity including airports. This guidance is the cumulative total of information provided by 1200 individual groups with over 60,000 members (the AF would be considered a group and an individual AF base would be considered a member). EPA required all representative samplers to analyze their storm water discharges for the basic NPDES parameters including BOD_5, COD, oil and grease, TKN, nitrate + nitrite as

nitrogen, pH, and total phosphorus. In addition to these parameters, sampling facilities analyzed their discharges for any pollutant they believed to be present (EPA, 1993:61150). The following table includes AF data submitted to the EPA as representative storm water pollutant concentrations in accordance with Part 2 of the group application:

Table 2.4
Air Force Storm Water Sample Data (1992)

Parameter	Unit	Composite Range (Mean)	Grab Sample Range (Mean)
Total Suspended Solids	mg/L	4-312 (71.07)	4-650 (181.49)
BOD_5	mg/L	2-42 (12.61)	1.0-18.45 (7.52)
COD	mg/L	5-60 (24.84)	5-225 (48.25)
Fecal coliform bacteria	MPN/100 ml	Not tested	Not tested
Nitrogen (total as N)	mg/L		
TKN		0.19-3.0 (1.19)	0.21-3.30 (1.23)
Nitrate+Nitrite		0.12-15.0 (1.39)	0.11-2.46 (.55)
Phosphorus (total as P)	mg/L	0.04-0.57 (0.25)	0.01-0.80 (0.29)
Oil and Grease	mg/L	0.8-2.90 (1.83)	0.2-5.8 (1.83)
pH*		6.8-9.4 (8.0)	5.0-9.4 (7.03)
Metals	µg/L		
Antimony		No detect	<10-39
Arsenic		No detect	<10-20.5
Cadmium		No detect	<1.0-3.4
Copper		<1.0-50.0	<5.0-15.6***
Lead		<14-20	<2.0-52.0
Selenium		No detect**	77-113****
Zinc		<14-94	<20-348

* pH is not necessarily a pollutant but included as an important characteristic of the runoff
** Selenium was a no detect but most samples were measured at <100 µg/L
***Most copper samples were measured at <50 µg/L
****Most selenium samples in the second set were measured at <100 µg/L

Although most AF bases complied strictly with the EPA requirements, detection levels varied widely throughout each sample set for those pollutants not regularly monitored

under the typical NPDES permit. Samples that were extreme or were obviously incorrect were discarded.

The trace metals portion of many of these sampling efforts were not standardized with detection levels of 50 µg/L and 100 µg/L, providing limited insight on the actual concentrations below these limits. Such non-standardized data collection for trace metals is not surprising since the EPA did not specifically require trace metal testing as pollutants of concern for airport type facilities, but concentrated on de-icing glycols and their increased BOD effects. This lack of emphasis stems from recent waste water concerns about immediate detrimental effects of pollutants such as BOD, COD, and nutrients such as nitrogen and phosphorous on receiving water quality which are also primary concerns of municipal waste water. These pollutant effects are seen almost immediately, through visible water quality degradation, algae blooms, and fish kills. The toxicity of metal accumulation on the other hand, can take years to become visible. However once such level of accumulation is reached, its effects are usually irreversible. This is not typically the case with pollutants resulting in high BOD and COD loading such as de-icers.

Storm Water Effects - The pollutants found in storm water have a wide range of effects on receiving waters which were summarized by the EPA in a 1984 report to Congress.

Table 2.5
NURP Water Quality Impacts From Non Point Pollutants

Pollutants	Water Quality Impacts
Sediments	- Decrease the transmission of light through water - Direct respiration and digestion effects on aquatic life - Decrease in viability of aquatic life - Decrease in value for recreational and commercial activity - Increase in drinking water costs - Examples include sand, silt, clay and organic materials

Salts	- Destruction of habit and food source plants for fish species - Reduced suitability for recreation through higher salinity levels (skin/eye irritation) and higher evaporation rates - Affect quality of drinking water
Pesticides/Herbicides	- Hinder photosynthesis in aquatic plants - Lower organism's resistance and increase susceptibility to other environmental stressors - Can kill non-target species - Can bio-accumulate in tissues of fish and other species - Some are carcinogenic and mutagenic and/or teratogenic - Reduce commercial/sport fishing and other recreational activities - Health hazard from human consumption of contaminated fish/water
Nutrients -Phosphorous -Nitrogen	- Eutrophication, or "promotion of premature aging of lakes and estuaries" - Nitrates can cause infant health problems - Reduced oxygen levels can suffocate fish species - Interference with boating and fishing activities - Eliminate submerged aquatic vegetation and destroy habitat and food source for aquatic animals and waterfowl
Metals	- Accumulate in bottom sediments, posing risk to bottom feeding organisms - Bio-accumulate in animal tissues - Affect life spans and reproduction rates of aquatic species - Affect water supplies and recreational and commercial fishing
Bacteria	- Introduce pathogens (disease-bearing organisms) to surface waters - Reduce recreational uses - Increase treatment costs for drinking water - Human health hazard (US EPA, 1984: 1-10, 1-11)

Legislative Action - It is quite obvious from the above impacts, that storm water prevention and mitigation is very important to continued quality of both ground and surface waters receiving storm water discharges. The EPA's decisions and forthcoming promulgation of regulations for storm water producers are expected to impose similar limitations already enforced by current NPDES permits. A recent edition of Water/Engineering & Management carried an article which made a startling prediction for the future of storm water containment and regulation. The last sentence of the article on a newly constructed postal facility required to have storm water containment read, "Future environmental law will eventually require every property owner to implement contaminant/containment procedures (Leise, 1991:28)." Although the Federal Register does not say anything about the common homeowner's contribution to storm water runoff

yet, it does currently list 30 specific industrial processes which will be regulated under Federal law and even more should be expected under State and Local statutes.

The future emphasis on regulating storm water discharges will be similar to the current focus in the hazardous waste generation industry, that of pollution prevention. Storm water flows cannot be eliminated regardless of which BMP is employed since precipitation events will continue to cause such flows, however precautions can be taken to eliminate the hazardous constituents so familiar to storm water flows. If the storm flow does not contain hazardous pollutants, then the storm water volume is the only concern factor. The Federal Register reiterates the importance of pollution prevention on non-point source pollution:

> The pollution prevention approach in today's proposed general permit focuses on two major objectives: (1) To identify sources of pollution potentially affecting the quality of storm water discharges associated with industrial activity from the facility; and (2) to describe and ensure implementation of practices to minimize and control pollutants in storm water discharges associated with industrial activity from the facility and to ensure compliance with the terms and conditions of this permit (EPA, 1993:61162).

Further on in this same document, the following concerning the viability of pollution prevention appears:

> EPA believes the pollution prevention approach is the most environmentally sound and cost-effective way to control the discharge of pollutants in storm water runoff from industrial facilities (EPA, 1993:61162).

From these statements, it would seem obvious that Federal regulatory attitude on storm water is to prevent their contamination early on. Such prevention measures can include a base wide survey to identify potential problem areas as was mentioned earlier in this chapter.

The Constructed Wetland Option

Why Constructed Wetlands? - Wetlands, both natural and constructed, have been used to treat a variety of waste waters for many years, but much of this treatment occurred with little or no knowledge of the exact processes that actually purified the water. Eric Livingston reinforces this idea, with the following statements:

> Unfortunately, the use of wetlands for storm water management involves a large degree of uncertainty. Little scientific information is available concerning the short- or long-term effects on wetlands, their natural functions, or associated fauna from the addition of storm water. Use of wetlands for urban storm water management should not be considered a panacea to storm water problems. Much remains to be learned (Hammer/Livingston, 1990:253).

Only within the past decade has enough information been made available for scientists and waste water engineers to adequately describe the wetland processes for the purpose of design for specific storm water pollutant loadings. Even today, many of the processes of wetlands are not fully defined and research continues to describe the long term effectiveness of such treatment systems. This is one of the primary reasons naturally occurring wetlands are not allowed to be used to treat waste waters. In fact, wetlands are currently the only habitat in the United States which are protected by law. This is a landmark regulatory change in ecosystem and species protection since no separate or single species is protected under this law, instead the focus has changed to protection of an entire ecosystem to preserve the biodiversity within. Such "landscape" type protection approaches may well be only the tip of the iceberg as far as the future of biodiversity and species protection (Cox, 1993:300). These natural ecosystems provide a much too important habitat for many unique and endangered species to allow experimentation with water pollution treatment. Williams and Dodd reported that 16 % of endangered mammals, 31 % of threatened and endangered bird species, 31 % of endangered and threatened reptiles, and 54 % of threatened and endangered fishes are dependent on wetlands or found in freshwater wetland habitats during part of their life cycle

(Hammer/Feierabend, 1990:115). This valid restriction forces pollution control designers to create new wetland treatment systems for waste water treatment. As mentioned before, these created wetlands rarely have the plant and animal diversification found in most natural wetlands. However, a recent study that compared microbial populations in CWs to microbial populations in naturally occurring wetlands found very similar microbial diversity and population densities (Duncan, 1994:304). CWs may not contain the biodiversity levels observed in natural wetlands, however they do have an obvious advantage over such wetlands, that of control. All wetland systems are based on natural microbial and hydrologic processes, a much larger degree of control is attained over a CW versus a natural wetland. This greater control allows the designer to create optimum start-up conditions with respect to plant selection, hydrology, soil type, etc., for a specific pollutant loading. CWs also allow the operator or maintainer to change these same parameters to optimize conditions and efficiencies as external changes such as temperature and water input variations are realized.

Wetland Populations - Vital to the effective function of any wetland are the microbial and plant biomass populations within its boundaries. The microbial and plant populations within a wetland are directly responsible for its pollutant removal and purification processes. These populations are the primary difference between a CW and other types of best management practices such as sedimentation ponds. Sedimentation ponds may indeed have microbial populations of substantial magnitude, however their numbers pale in comparison with naturally occurring and CWs. Hatano and others found that microbial populations in unplanted gravel beds receiving storm water (sedimentation or detention pond) were orders of magnitude lower than CWs receiving similar storm inflows (Morishi/Hatano, 1993:545). Thus, wetlands have a much greater capability to degrade pollutants based on the sheer number of microbial organisms they sustain.

Table 2.6
Comparison of Microorganisms Found in the Rhizosphere and Gravel of Three Subsurface Flow Constructed Wetland Cells in August 1991

Substrate	Bacteria	Actinomycetes	Fungi
Gravel	0.6×10^6	3.1×10^4	0.6×10^3
Cattail gravel	1.6×10^6	1.4×10^5	4.0×10^3
Cattail rhizosphere	3.5×10^9	2.5×10^6	2.8×10^4
Reed gravel	1.2×10^7	2.8×10^5	1.1×10^5
Reed rhizosphere	0.6×10^9	1.3×10^6	1.6×10^6

Note - All values are expressed as colony forming units / gram of dry weight.

Plant populations found in wetlands are both diverse and large in number with net primary production and standing crop values equivalent to those of tropical rain forests. These large plant biomass and production values can be attributed primarily to the large amounts of nutrients that typically flow through wetlands transported by variable hydrologic flows. Plant biomass is of great importance to the wetland ecosystem since it provides food for many wetland species. Wetland plants take up nutrients such as phosphorous and nitrogen as well as pollutants such as metals from wetland sediment. Nutrients are used by the plant to grow and are stored within the plant, creating a large reservoir of nutrients that are released when the plant dies. Pollutants such as metals are not typically used to facilitate plant growth and tend to become locked into the plant biomass remaining unchanged until plant death and decay. Thus, the wetland's plant biomass represents a continually cycling reservoir of both nutrients and pollutants that is characteristic of the wetland sediment and water flows.

Directly related to the living plant biomass population is the production of plant litter and detritus in a wetland. Wetland plant decomposition generally refers to the disintegration of dead organisms into particulate form until the structure can no longer be recognized and complex organic molecules have been broken down into carbon dioxide, water, and mineral components. The rate at which wetlands break down plant biomass is highly variable depending on microbial population, temperature, and plant species. This variability was experienced by de la Cruz who studied decomposition rates in 30 species

of fresh water and 11 species of salt water wetland plants. Decomposition rates determined by the litter bag technique vary in fresh water species from 60 to 80 percent breakdown of material over a 90-day period and from 40 to 100 percent for a one-year period (Greeson/de la Cruz, 1978:162).

Wetland Processes -The basic pollutant removal functions found in any wetland system can be described by the following processes:

> 1. Sedimentation - This is one of the principal mechanisms of pollutant removal in wetlands. Storm flows fill the available pool area and particulate matter settles. Vegetation slows the incoming velocity, disperses the incoming water, and further enhances the settling/deposition process (Lakatos, 1987:690).
>
> The suspended solids discharged with treated waste water ultimately settle to the bottom. Settling is enhanced by flocculation and hindered by ambient turbulence. In some wetlands, turbulence is often sufficient to distribute the suspended solids over the entire water depth (Morishi/Tchobanoglous,1993:29).
>
> 2. Adsorption - This is a physical and chemical process by which dissolved pollutants adhere to bottom sediments and vegetation surfaces. Adsorption is a primary pollutant removal mechanism for wetland facilities, for both the more common pollutants (such as nutrients) as well as metals and even viruses (Lakatos, 1987:690).
>
> Many chemical constituents tend to attach or sorb onto solids. The implication for waste water discharges is that a substantial fraction of some toxic chemicals is associated with the suspended solids in the effluent. Adsorption combined with solids settling results in the removal from the water column of constituents which might not otherwise decay (Morishi/Tchobanoglous,1993:29).
>
> 3. Filtration - This occurs as particulates are mechanically filtered through sediments, vegetation, and biota in the wetland area. Densely vegetated wetlands offer substantial filtration area (as well as adsorption surfaces area). Filtration through vegetation and bottom soils can significantly reduce the migration of pollutants and bacteria along the length of the wetland (Lakatos, 1987:690).
>
> 4. Biological Assimilation - Wetland vegetation offers high pollutant absorption and, therefore, biological uptake potential as well as providing an environment for significant microbial activity. Plants take up pollutants through their roots, which then allows for further pollutant absorption within the plant tissues. Plants also

absorb nutrients and ionic compounds from the water via shoots and leaves (Lakatos, 1987:690).

5. Microbial Decomposition - This occurs both aerobically and anaerobically in the water column, on the plant surfaces and within the soil. BOD removal in wetlands, for example, is carried out by decomposing microorganisms. The bottom environment containing the wetland sediments at the soil/water interface is commonly aerobic and provides the necessary condition for denitrifying bacteria survival, which is a major part of the process for nitrogen removal. Heavy metals are converted to relatively insoluble sulfates in the reduced soils, which are characteristic of anaerobic conditions (Lakatos, 1987:690).

Bacterial conversion (both aerobic and anaerobic) is the most important process in the transformation of contaminants discharged to CWs. The exertion of CBOD and NBOD are the most common examples of bacterial conversion encountered in water quality management. The depletion of oxygen in the aerobic conversion of organic wastes is also known as deoxygenation. Solids discharged with treated waste water are partly organic. Upon settling to the bottom, they decompose bacterially, either anaerobically or aerobically, depending on local conditions. The bacterial transformations of toxic organic compounds is also of great significance (Morishi/Tchobanoglous,1993:29).

6. Chemical Decomposition - This mechanism involves such things as photochemical reactions, chemical oxidation and reduction which also occurs in a wetland type area (Lakatos, 1987:690).

Important chemical reactions which occur in wetlands include hydrolysis, photo-chemical, and oxidation-reduction reactions. Hydrolysis reactions occur between contaminants and water. Solar radiation is known to trigger a number of chemical reactions. Radiation in the near-UV and visible range is known to cause the breakdown of a variety of organic compounds (Morishi/Tchobanoglous,1993:29).

7. Volatilization - Volatilization is the process whereby liquids and solids vaporize and escape to the atmosphere. Organic compounds that readily volatilize are known as VOCs (volatile organic compounds). The physics of this phenomenon are very similar to gas absorption, except that the net flux is out of the water surface (Morishi/Tchobanoglous,1993:29).

These processes in the wetland affect each pollutant differently. Watson and others provide the following table which associates removal processes with individual pollutants (Hammer/Watson, 1990:321).

Table 2.7
Contaminant Removal Mechanisms in Aquatic Systems Employing Plants and Animals

Mechanism	Contaminant Affected	Description
Physical		
Sedimentation	P-Settleable solids S-Colloidal solids I-BOD, nitrogen, phosphorous, heavy metals, refractory organics, bacteria and virus	Gravity settling solids (and constituent contaminants) in pond/marsh settings.
Filtration	S-Settleable solids, colloidal solids	Particulates filtered mechanically as water passes through substrate, root masses, or fish.
Adsorption	S-Colloidal solids	Interparticle attractive force (van der Waals force).
Chemical		
Precipitation	P-Phosphorous, heavy metals	Formation of or coprecipitation with insoluble compounds.
Adsorption	P-Phosphorous, heavy metals S-Refractory organics	Adsorption on substrate and plant surface.
Decomposition	P-Refractory organics	Decomposition or alteration of less stable compounds by phenomena such as UV irradiation, oxidation, and reduction.
Biological		
Microbial metabolism	P-Colloidal solids, BOD, nitrogen, refractory organics, heavy metals	Removal of colloidal solids and soluble organics by suspended, benthic, and plant supported bacteria. Bacterial nitrification/denitrification. Microbially mediated oxidation of metals.
Plant metabolism	S-Refractory organics, bacteria, and virus	Uptake and metabolism of organics by plants. Root excretions may be toxic to organisms of enteric origin.
Plant absorption	S-Nitrogen, phosphorous, heavy metals, refractory organics	Under proper conditions, significant quantities of these contaminants will be taken up by plants.
Natural dieoff	P-Bacteria and virus	Natural decay or organism in an unfavorable environment.

P=Primary effect, S=Secondary effect, I=Incidental effect (effect occurring incidental to removal of another contaminant).

As is pointed out under the "incidental" remark above, many pollutants are affected by the primary processes which affect the larger particles to which they may be attached or come in contact with. The settling out of particles from the incoming waste water in the CW

has much the same effect as in the sedimentation basins and flocculation chambers incorporated by most sewage treatment plants. Smaller, typically slow settling particles become trapped by larger sediments that settle quickly on their way to the wetland floor (Gadbois,1989:15). Thus, mere sedimentation of larger particulate matter can have a complementary effect on other non-settleable pollutants. This incidental process is very important to trace metal removal in the wetland.

A wide range of sediment removal efficiencies can be found in wetlands, including CWs that actually are sediment sources. R. L. Knight and others have compiled a database of wetlands used to treat a variety of waste waters. The majority of these wetlands are used to treat municipal waste waters however their survey listed two free water surface (FWS) wetlands receiving storm water whose data are presented below.

Table 2.8
Selected Wetland Operational Data

System Name	Type	Record (Years)	Area (ha)	Flow (m^3/day)	TSS (mg/l) IN	TSS (mg/l) OUT
Hidden Lake SW	FWS	0.75	3	-	6.4	13
Mays Chapel	FWS	1	0.24	160	85.4	33.9

The average sedimentation efficiency for all wetland treatment systems (whether natural or constructed) in this survey resulted in a value of 68.8 % (Morishi/Knight, 1993:42-47).

Trace Metal Removal - Although removal and cycling of pollutants such as BOD, COD, and primary nutrients in CW systems have been fairly well documented, trace metal removal processes have received less attention. Generally, removal processes include sedimentation, filtration, adsorption, complexation, precipitation, plant uptake, and microbial mediated reactions, especially oxidation. However, wetlands typically provide conditions that optimize metal removal in two primary ways:

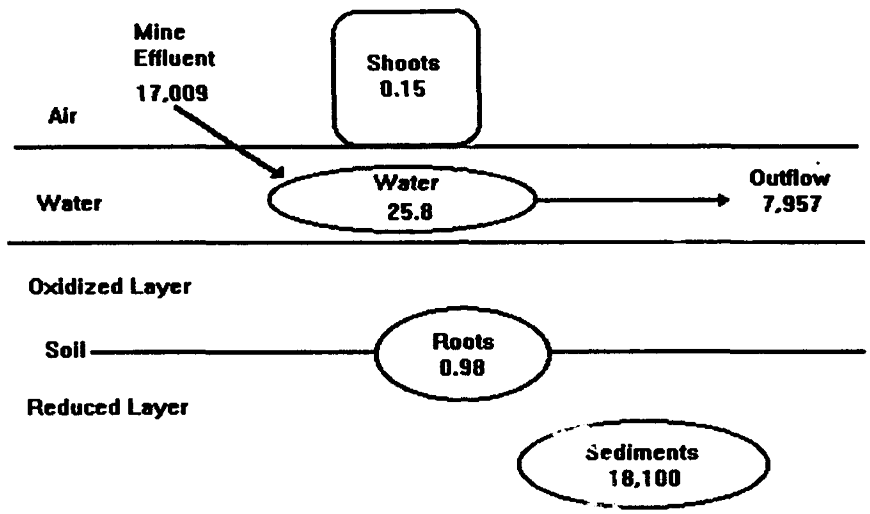
1) They provide a great reduction in water velocity entering the wetland which allows sedimentation to occur.

2) They provide abundant binding sites for the metals to attach to (Gadbois, 1989:15)

Metals tend to sorb onto organics and clay particles and settle along with these particles. Thus, a partial treatment (removal from the water column) for heavy metals is similar to other pollution forms - settling time in a calm basin. This settling is enhanced by flocculation with material to which the metals can sorb. Mesuere and Fish present such conclusions about copper concentrations in storm water from a parking lot catchment area. The authors found that much of the copper flowing into the detention pond system (consisting of three cells in series) settled out of solution in the first detention pond with smaller concentrations proceeding on to the secondary cells. Similar results have been observed with concentrations of lead which tends to have a high affinity for particulate versus dissolved states (Mesuere, 1989:136). Although high sedimentation rates may be appropriate for some metals such as copper and lead, other metals such as cadmium and some species of copper can be found primarily in the dissolved state and largely unaffected by sedimentation (Hvitved-Jacobsen, 1987:140).

Much has been learned about iron (Fe) and manganese (Mn) removal processes and efficiencies in CWs through work done by the Tennessee Valley Authority (TVA) by way of experimenting with coal mine drainage. Researchers have reported variable metal removal efficiencies from these CW endeavors. Removal efficiencies of over 90 % have been experienced as well as efficiencies near zero. Figure 4.10 shows the various stocks of iron (g/m^2) in a CW receiving acid mine drainage (Hammer/Faulkner, 1990:62).

Figure 2.1
Iron Stocks From a CW Receiving Mine Effluent



The available data seems to point out limited lifetimes for such CWs, greatly dependent on pollutant loading concentrations and soil substrate (Hammer/Brodie, 1990:209; Hammer/Watson, 1990:337; Hammer/Silver, 1990:757).

Other studies have concentrated on the trace metal removal capabilities of CWs on pollutant loadings from non-coal mining applications. Trace metals of concern from these scenarios are more related to those found in urban storm water, however concentrations are orders of magnitude greater than those experienced in most urban environments. Trace metals such as nickel (Ni), copper (Cu), cobalt (Co), and zinc (Zn) in these scenarios originate from metal mine drainage and stockpiles. Wildeman and Laudon experimenting with a variety of plant types and organic based soils, postulate five different possible removal mechanisms available in CWs receiving such acidic metal mine drainage:

1) Filtering suspended and colloidal material from water.

2) Uptake of contaminants into roots and leaves of live plants.

3) Adsorption or exchange of contaminants onto soil materials, live plant materials, dead plant materials, or algal materials.

4) Precipitation and neutralization through the generation of NH_3 and HCO_3- by bacterial decay or biologic material.

5) Precipitation of metals in the oxidizing and reducing zones catalyzed by bacterial activity.

The results from this study have not identified one dominant process, however the authors have postulated that mechanism five above may be dominant based on their analysis of metal removal geochemistry observed at the Big Five Tunnel site (Hammer/Wildeman, 1990:224). Eger and others have experimented with CW (cattails in peat) removal of similar trace metals emanating from the Dunka mine in Minnesota. Results show high removal efficiencies that can be maintained if the substrate material (peat or other organic material) is periodically removed and replaced. The authors postulated that such CWs could be used in this capacity indefinitely if removal rates are closely monitored and the substrate metal loading is not exceeded (Hammer/Eger, 1990:783; Morishi/Eger, 1993:178). Such CWs seem to function efficiently in regards to trace metal removal at almost any location around the world. The following table quantifies the results of wetland (reed swamp) purification of trace metals from the Qixinghe River in China (Ma, 1993:298):

Table 2.9
Capacity of Reed Swamps to Purify Water (μg/kg)

	Al	Fe	Be	Cd	Co	Cu	Cr	Mn	Ni	Pb	V	Zn
Qixinghe River water	280	400.1	0.16	.004	0.38	13.8	0.48	83.1	1.78	2.22	1.51	14
Reed swamp water	11	28.3	n.d.	n.d.	.176	3.92	.159	4.53	0.77	0.44	0.72	4.78
Purifying Capacity, %	96	92.7	100	100	71.5	71.5	66	94.5	59.4	80.2	52.1	65.8

n.d. = not detected

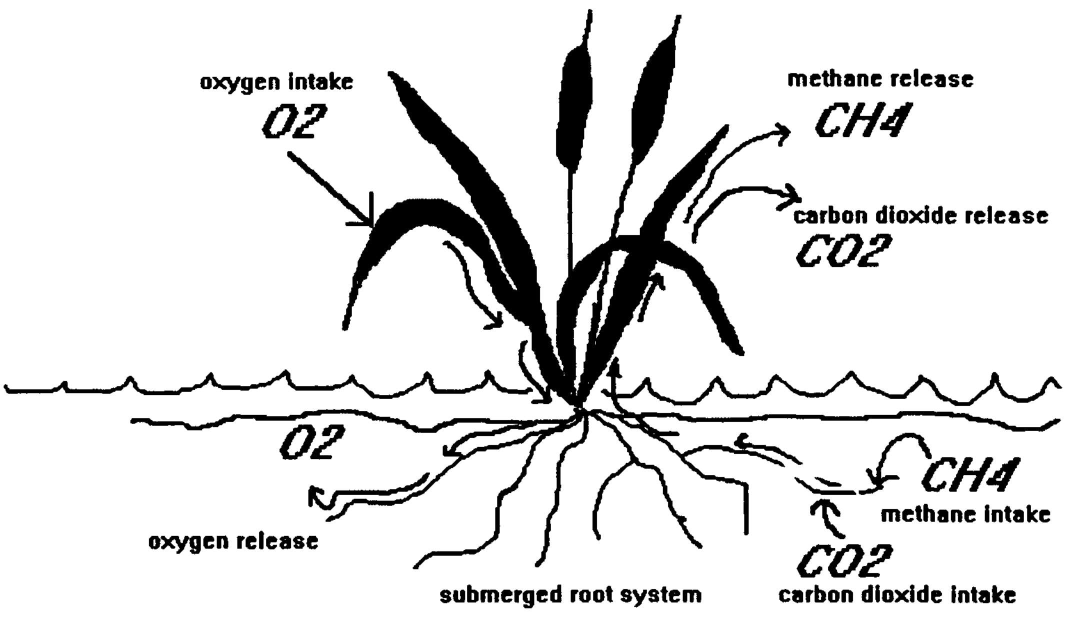
Such high removal efficiencies are typical of CW systems which are relatively new or have very low pollutant loadings. There is no mention about how long such removal efficiencies have been in effect, nor how long such efficiencies are expected to continue.

Guidance on wetland basins for storm water treatment has been provided by numerous organizations, including the State of Maryland's Sediment and Storm water Division. The trace metal removal processes as seen in the Washington DC area seem to have a familiar flavor as those described elsewhere. The authors of this guidance postulate that metals may be associated with suspended solids by cation exchange and adsorption to hydrous oxides of iron, aluminum, and manganese. In addition to these two removal processes, metals bind with a large number of anionic molecules, organic and inorganic, in the chelation process. Organic substances play an important role in the chelation process because they tend to increase solubility of trace metals and may be the primary cause of such solubility. In anaerobic wetland soils the products of anaerobic decomposition include a wide variety of partially oxidized organic molecules, and these molecules are important in the solubility of trace metals in anaerobic sediments. In addition, trace metals are also adsorbed by hydrous oxides of iron, aluminum, and manganese under aerobic conditions, and released as these metals undergo changes in oxidation states under anaerobic conditions (Sediment and Stormwater Division, 1991:42).

The authors of this guidance point out that sedimentation and adsorption through oxidation/reduction with certain metals seem to be the two primary metal removal processes. Sedimentation is an easily understandable and expected removal mechanism common in almost all wetlands for a variety of pollutants. However trace metal oxidation/reduction at the soil/water interface seems to be less likely at first glance. Oxidation/reduction reactions basic to trace metal removal in a wetland are highly dependent on the microbial communities present in the wetland water. Such communities include both aerobic and anaerobic organisms. Anaerobic conditions would seem likely to prevail in a wetland or any other water body since typical oxygen concentrations in water are around 8 ppm. Such low oxygen concentrations would seem to be quickly

depleted by any initial aerobic microorganisms creating anaerobic conditions in both the wetland water and soil below the water level. Wetland water and sediment processes are indeed dominated by anaerobic conditions, however wetland plants provide necessary "pockets" of oxygen for the aerobic microbial communities existence. Many wetland plants are unique in their capacity to channel oxygen below the water surface creating a thin aerobic layer around their rhizome. This oxygenated area of the wetland provides the breathing space for the multitude of aerobic organisms busily degrading trace metals as well as other pollutants such as BOD. In fact, much of any wetland's pollutant removal capability can be linked to the plants in these unique ecosystems ability to maintain large numbers of microorganisms below the water surface. This process is depicted in Figure 2.2 (Morishi/Brix, 1993:393):

Figure 2.2 - Plant Aeration/Diffusion of a Submerged Wetland Soil



Metal Accumulation and Toxicity - Although CWs seem to provide efficient and manageable removal of trace metals from incoming water sources, some concern about

metal accumulation and toxicity within the wetland ecosystem is in order. In fact, L. E. Gadbois summarizes the feasibility of CW's to treat trace metals in runoff pollution at Naval facilities with concern about plant uptake and further incorporation into the food chain. "Wetlands, therefore appear to have questionable value for treatment of metals in runoff. The total quantity reaching the adjacent open water will likely be reduced, but that which does reach open water will likely be in a form more readily passed into the food chain. If metals are a major contaminant in the runoff, an alternate treatment method is advised (Gadbois, 1989:15)." Others have also realized the effects of metal accumulation in wetlands and the possibility of both floral and faunal toxicity. Worldwide attention was focused on selenium (Se) in the environment in the mid 1980's, when subsurface agricultural drainage waters were used for creation and management of wetlands in the Kesterson Reservoir National Wildlife Refuge, California. Studies of this wetland showed that Se bioaccumulated in plants and animals to levels that adversely affected wildlife (Masscheleyn, 1993:2235) The State of Maryland guidance provides this caveat to using CWs for trace metal removal. "Trace metals can accumulate in sediments and in the food chain, and thus have the potential to reach levels that may be toxic to human beings or other organisms. Serious poisoning by cadmium and mercury has occurred (Sediment and Stormwater Division, 1991:11).

Although trace metals in the environment from anthropogenic sources have become of great concern in the past two decades, most if not all trace metals found in storm water runoff are also naturally occurring. In fact, these metals are of great importance to all living creatures in the biosphere. The problem with trace metals is the fact that they do not degrade and dissipate readily as other pollutants do. Copper is an essential element for birds and mammals, being a component of several enzymes. Excessive intake of copper by mammals results in accumulations in the liver. Lead is accumulated in the skeleton of mammals, where excess accumulation results in the loss

of membrane permeability of kidney, liver, and brain cells. Loss of function of these organs may result. Zinc is one of the most abundant trace metals in mammalian tissue, but excess amounts may cause metabolic dysfunction. Cadmium, although not readily found in typical storm water, has a high affinity for accumulation and potential toxicity. The EPA stated that all of these metals are toxic to aquatic life and can become concentrated in the food chain (Sediment and Stormwater Division, 1991:12).

Such toxicity concerns stem primarily from the uptake of metals from wetland sediment by plants and their removal from the wetland by way of herbivore consumption as well as animals which feed directly on or around the wetland sediment. The fact that plants and animals do take up and accumulate metals has been fairly well documented, however specific uptake rates, equilibrium concentrations, uptake factors, and resulting toxicity are much less defined and highly specific to type of metal, soil, plant, and environmental conditions. Field results showing a high degree of variability from a wetland site receiving storm water are tabulated below (Morishi/Shutes, 1993:411-412):

Table 2.10
Metal Concentrations of Solution, Sediment, Typha Root, Rhizome, Leaf and Totals (ppm)

Location of Metal	**Cadmium**	**Copper**	**Lead**	**Zinc**
Solution	0.009	0.053	0.036	0.137
Sediment	12.4	220.1	841.2	778.9
Root	6.0	410.8	95.8	164.4
Rhizome	3.7	220.1	31.9	42.9
Leaf	3.4	146.7	18.8	35.7
Total Plant Biomass	**13.1**	**777.6**	**146.5**	**243.0**

No reference as to how long this site has been receiving storm water is mentioned in the Shutes article, however an assumption is made about certain metals reaching maximum levels in certain plant parts. This fact would probably be representative of a site that has received storm water for some time greater than one year. Regardless of this oversight, the data shows a wide variance in metal accumulation due to type of metal as well as the location of the metal concentration.

If the CW soil does become saturated with trace metal accumulations, a toxicity for some or all plant species could potentially be reached. In six-week experimental studies performed with freshwater wetland plants in the presence of dissolved Zn, Cd, Ni, Pb, and Cr (0.5 and 1.0 ppm), W. James Catallo found both growth inhibition and mortality in two different species (Catallo, 1993:2215). High accumulations of metals usually tend to decrease biodiversity first, eliminating those less hardy plants and promoting domination of those better able to adapt. This scenario is not desirable, since plant biodiversity is one of a wetland's most important features. Much less desirable is the possibility of complete toxicity of the wetland plant biomass, in which case neither the wetland ecosystem nor its pollutant removal capacity exists. Most research efforts however, show that even under high metal accumulations in wetland soils, some plant species will survive. Shutes and others found high metal concentrations to exist in both reed and cattail plants over an eight-week period with no observable effect.

Table 2.11
Concentrations in Typha Tissues After 8-week Metal Dosing Experiment
With No Observable Toxic Effect in ppm (Shutes and others, 1993)

	Cadmium	Copper	Lead	Zinc
Leaf	30	25	45	40
Rhizome	125	100	60	125
Root	650	200	225	670

Therefore the problem with metal accumulation in the wetland sediment as it applies to plant biomass toxicity is a decrease in plant species diversity, not so much in total plant biomass elimination.

Similarly, another problem with metal accumulation in the soil, is the reduction of microbial diversity, not usually complete removal of all such organisms. Microbial populations have been shown to be able to exist in extremely toxic conditions, however such organisms are not diverse and can be more easily eliminated by secondary perturbations to the system. The Catallo article mentioned above states that microbial

systems exposed to organic and metallic pollution have been shown to undergo at least temporary decreases in species diversity, dominance of adapted, generalist, or resistant populations, as well as changes in metabolic function (Catallo, 1993:2213). Diversity allows the system to rebound and recover if conditions in the wetland change, for better or worse. Without such diversity, additional small changes could have catastrophic results in microbial population existence much less wetland efficiency and overall function.

Metal accumulation in wetland soil then can have adverse effects on the wetland populations; however an additional concern is the potential for such contamination to reach species outside the wetland boundaries. Animal species that feed on wetland plants and animals can also be affected by metal accumulation in the wetland. This concern is reflected in regulatory levels of metals in sewage sludge used for compost. Certain metal concentrations in sewage sludge have been determined to cause unacceptable levels of risk to the persons using the sludge as compost material on residential lawns and gardens due to plant uptake and potential human ingestion. Likewise, wetland soils grow plants which in turn are ingested by wetland animals and migratory birds. Table 2.11 lists state and federal limits for metal concentrations in sewage sludge used for compost.

Table 2.12
EPA and Minnesota Pollution Control Association (MPCA) Metal Standards in Sewage Sludge Used as Compost Material in ppm

	Cadmium	Chromium	Nickel	Lead	Zinc
EPA Pollutant Concentration Limits for Sewage Sludge	39	1200	420	300	2800
MPCA Standards	10	1000	100	500	1000

It is logical to assume that concentrations of such metals in wetland soils may also pose hazards for plants and animals living and feeding in the wetland as well as humans in frequent contact with the wetland soil.

Wetland Modeling

In their article on wetland modeling, Mitsch, Straskraba, and Jorgensen ask and answer the question--Why model wetlands? (Mitsch, 1988:1) Recent and not so recent efforts have attempted to model wetland ecosystems with varying results and recommendations for future attempts. Wetland biologists and mathematicians around the world have sought to model wetlands in part or as a whole for various purposes. However, their success in this field has been less than spectacular, especially in the aspect of contaminant transport and cycling in a wetland. A June 1993 article from Environmental Toxicology and Chemistry states the following summary of the state of wetland contaminant transport models. "At this writing there are no ecosystem models that are capable of predicting contaminant transport and fate in wetlands. In the future, more resources need to be provided to support modeling contaminant transport and fate in an effort to assess wetland sustainability (Dixon, 1993:2290)." Mathematical depictions of these diverse and changing systems and comparison to actual results brings about learning, albeit, many times through failure. Models allow the user to quickly and cheaply assess the many possibilities of additions or deletions of a myriad of variables that directly or indirectly affect the wetland ecosystem. William Mitsch affirms this statement in his Wetland Modeling text, "The model demonstrates how modeling can be used with the theory already developed in a decade of studies to "experiment" with wetlands in a way that would be impossible to observe in field studies (Mitsch,1988:129)." Hypothetically, they can be wonderful tools that accurately simulate the wetland process, however no model has been created that exactly predicts or represents the wetland ecosystem without certain limitations and assumptions. To be of any use however, wetland models must be created to emphasize important variables and processes particular to the focus of the project while assuming that other processes are unimportant and can be left out or assumed to be constant. These assumptions are vital to

wetland models and simulations due to the enormous diversity encountered in the simplest wetland process. If, however, these assumptions can be made without deletion of important variables, an accurate representation with respect to those aspects of interest of wetland function can be accomplished. Thus allowing the modeler to predict potential long term effects that have not yet been observed in the field.

Costanza and Sklar conducted a review of 87 mathematical models of freshwater wetlands and shallow water bodies. The models were evaluated and ranked on their effectiveness to simulate a wetland ecosystem (or part of it) using the limited resources available to its creators. However, none of the models included in their review, nor any other known by Dixon and Florian were developed to track contaminant mobility and effects (Dixon, 1993:2281). The models that have been developed address nutrient cycling, primary productivity, and hydrodynamics because of the role wetlands play in tertiary wastewater treatment. In spite of the concern that various contaminants have been found in industrial sewage effluent, wetland ecosystem modeling has not addressed these problems to any great extent.

It seems that both wetland systems and individual contaminant transport, uptake, and toxicity have been successfully modeled, however the two fields of research have not yet been effectively incorporated. An example of such separate modeling directions is given by Chapra and Boyer in their article entitled, "Fate of Environmental Pollutants". Their article describes a multitude of models and research efforts which focused on the fates of pollutants in natural waters (Chapra, 1992:581). However, most if not all, the described models have focused on a particular part of a larger ecosystem setting such as wetland hydrology or net primary production. One reason so little is available on modeling contaminant transport and toxicity within a wetland ecosystem is the complexity that is involved in combining both the wetland ecosystem and the individual processes that are involved. The complexity of wetland processes and the difficulty in

modeling these processes require integration of many specialized disciplines to understand and develop models that accurately reflect the processes occurring in wetlands.

It is apparent that contaminant transport and toxicity models of wetland ecosystems have not yet been effectively developed although the individual components necessary for their creation are currently available. It would also seem to be reasonable to assert that such efforts of meshing both wetland ecosystem and contaminant transport processes could be a rewarding effort in the prediction of long term effects on these unique and valuable resources. Problems of how individual components within the wetland system interact with and are influenced by each other and the magnitude of these affects, whether synergistic or antagonistic must be overcome. One possible solution to these problems could be the incorporation of multidisciplinary teams of environmental toxicologists, chemists, biochemists, ecologists, engineers, and computer programmers to establish models for each type of wetland. Thus allowing other modelers to apply their specific conditions to these generic model structures (Dixon, 1993:2290). Such models need to be understandable and easily adaptable to individual users needs to be of any use which is highly dependent on the team effort and the modeling software that is chosen to create such a model.

One such modeling software which allows the user to easily depict and explain the modeling process while evaluating complex systems is Stella II produced by High Performance Systems of Hanover, NH. This type of software allows the user to model almost any type of system or flow with accuracy and ease making it an ideal choice for the environmental processes involved in modeling a wetland ecosystem. The Stella II software provides many built-in modeling functions and much literature information explaining how one might go about simulating different processes in reality. One such process described in the Stella II User's Guide is the co-flow process (Stella II User's

Guide, 1990:128) Although not implicitly correct according to System Dynamics principles and methodology due to the time lag inherent when a rate influences a rate, this process can be used to simulate trace metal transport and uptake within the wetland ecosystem (Howell, 1994). The co-flow process permits the modeler to show the interdependence of the trace metal flow on its primary transportation vehicle, the wetland hydrology. This process is one possible answer to the complex problem of intertwining wetland ecosystem modeling with its individual sector contributions. In fact its application is not limited to trace metal transport, but can help define any process in the wetland based on the wetland hydrology. Dixon and Florian's modeling article noted above qualifies this notion: "Sediment transport processes depend on the underlying hydrodynamics. It is essential therefore to have verified hydrodynamic models before accurate modeling of sediment transport is possible (Dixon, 1993:2287)." Likewise, contaminants dependent on the sedimentation process, such as pollutants that are attached to particulate matter, will depend on both the hydrologic and sedimentation flows within the model. Once the hydrology part of a wetland model is defined the other individual wetland component parts can be added and their specific relationships described. This modeling process should begin to allow the marrying of the "big picture" wetland ecosystem dynamics with the microscale sectors that make up the wetland's pollutant removal capability.

This co-flow process and variations thereof are at the heart of the model discussed in the next chapter. This process is not the only process used in the model, however it may be the most controversial and least accepted of the system dynamics modeling processes used. The co-flow process is defined by a rate (hydrologic flow rate) influencing other rates such as the sedimentation and trace metal inflows and outflows. Such methodology is not in strict adherence with system dynamics doctrine which does not allow one flow rate to influence another. This rationale is based on the fact that a rate

is never actually measured exactly in models or reality, instead what is measured in reality is an average rate. This fact can cause problems in modeling due to the delay involved in averaging the first rate and then sending it on to affect the second rate and third if necessary. This delay can cause a modeling situation to arise that predicts that sediment or metals will still be flowing into or out of the system while the water flow has already stopped one time increment behind. This potential disconnect can have drastic effects if the chosen time increment is large however it becomes much less obvious as the time increment becomes small in comparison to overall simulation time frame. In fact, William J. Mitsch's "Productivity-Hydrology-Nutrient Models of Forested Wetlands," chapter 7 of his Wetland Modeling text, describes a wetland model in which one flow rate directly influences another (Mitsch, 1988:115-131). This model attempts to describe the effects of nutrients on forested wetland production and Mitsch uses the co-flow process because the incoming nutrient supply is dependent on the water fluxes which transport it. Although not strictly correct by system dynamics evaluation, the model does adequately serve its creator's purpose due to its chosen time increment.

Constructed Wetland Design

The design of CWs has to date typically been derivative rather than innovative. Many early attempts at wetland design consisted primarily of oxidation ponds with wetland plants placed in them. However, such early attempts at CW application to waste water treatment, regardless of outcome, have laid the foundation for much more efficient and predictable results from such treatment systems. The design methodology for CWs intended to treat waste water of any type has primarily focused on optimizing conditions to remove pollutants such as BOD and nutrients since these are typical pollutants of concern in municipal waste water. Such design methodology is not necessarily counterproductive to trace metal removal efficiency in storm water, however certain

design steps can be incorporated into a CW to help optimize trace metal removal as well as the typical waste water pollutants. These steps are derived from both knowledge of the storm water flows and concentrations as well as the plants, microbes, and soil types used to treat such flows.

Storm Water Specific Design - Typically all storm water events produce their highest concentrations of pollutants during the initial "washing" of the land surface. This initial runoff pollutant concentration in storm water is often referred to as the "first flush" effect. The first flush phenomenon results from two important aspects:

1. The hydrograph--or the way that rainfall washes a site during a storm event.

2. The pollutant buildup concentrations - Current theory and testing show that pollutants which have accumulated on the land surface between rainfall events have their heaviest washoff concentrations at the beginning of a new storm. This heavy buildup is easily washed off with even a minor amount of rainfall (Lakatos, 1987:691).

The combination of these two factors cause the first amounts of storm water entering a CW to be highly polluted and usually the governing conditions for design. However, if a storm event continues, the concentration of pollutants greatly decreases and the polluted water already in the CW becomes diluted. Taylor and others research with acid mine drainage in Alabama, showed the first flush factor to be a real regulatory problem, especially from storm events that are observed during the dry season where precipitation is sporadic. If long periods elapse between rainfall events, pollutants can build up and deliver extremely high concentrations when precipitation does occur (Morishi/Taylor, 1993:144).

Storm water presents problems for conventional waste water treatment systems, however there are also general caveats that should be considered when applying a CW as a storm water best management practice. In response to a questionnaire completed by

storm water management and wetlands professionals, these performance considerations were repeatedly mentioned:

1. The effect that first flush amounts will have on the capacity of the wetland system to remove pollutants for long periods of use.

2. The possibility of scouring the retained pollutants and sediments, resulting in actual increased impacts on downstream receiving waters; this scouring is projected by many respondents to result from ineffective design of wetland systems, particularly concerning inflow dispersion and velocity reduction.

3. The effect of sediment buildup in the wetland system, which would impact not only the available volume and surface area for pollutant removals, but also the vegetation species.

4. The effect of controlled water level fluctuation and detention time on native wetland species cycling and reproduction.

5. The possibility that a wetland storm water management site could create a toxic environment to wildlife and vegetation (Lakatos, 1987:692).

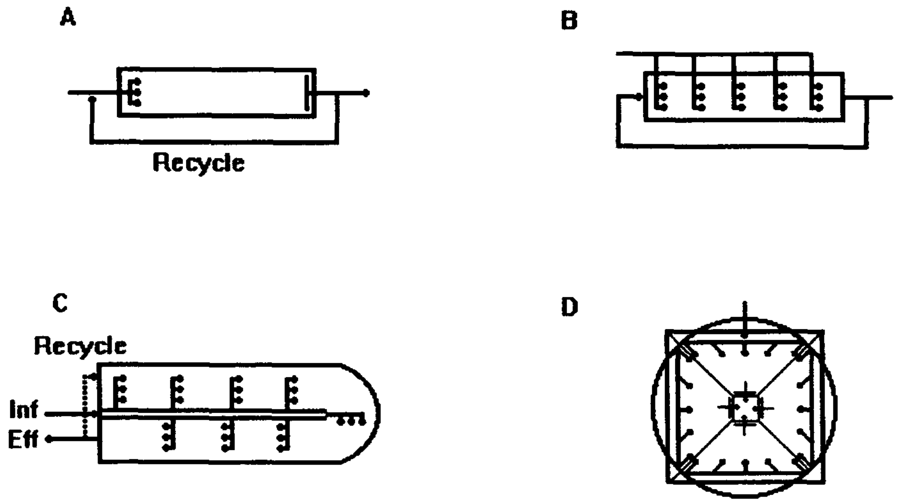
These considerations must be anticipated and their solutions designed into the CW prior to start-up, or the CW could not only not meet its intended goal of pollutant removal, but create a hazardous and costly clean-up site. The first consideration can be avoided by designing a large enough CW system to handle storm flow concentrations and volumes. This may be the most complex problem since it involves both knowing the storm water characteristics and providing enough area and money to create an adequate treatment facility. The latter of which may not always be possible.

The second consideration above deals with the system design and capacity. Small CW systems will invariably need more efficient designs than those with the luxury of having a greater area and hence capacity. The fact that a CW is small, however does not mandate that its operation be only mildly effective, its designers however must be more innovative in creating CW conditions which slow water flows and provide sufficient filtration. Four such innovative designs are shown below, all of which incorporate some

type of recycle flow. This design feature allows a smaller CW to handle larger flows, since the CW gets a "second chance" at reducing storm water pollutant concentrations. Such designs do of course have a down side, that of additional pumping equipment to recycle the water flow, but those locations restricted by limited land area would do well to consider such a modification (Morishi/Tchobanoglous, 1993:26).

Figure 2.2

Alternative Flow Diagrams for Constructed Wetlands



A, plug-flow with influent distribution and recycle; B, step-feed with recycle; C, step-feed with recycle in wrap-around pond; and D, peripheral feed center drawoff.

On the other hand, large CW systems are not immune to inefficient operation. Flow channelization in any size CW can quickly create conditions which transport inflowing storm water to CW discharge without allowing purification processes to be realized. Thus, larger CW systems do have the advantage of providing room for error with greater capacities, however smaller CW systems can be just as effective if designed properly.

The third consideration listed above can usually be remedied through the use of a sedimentation basin. Much of a storm water's incoming suspended solids fraction and

other important settleable pollutants can be quickly removed through sedimentation times of a day or less (Akan, 1992:381). If adequate sedimentation and interception structures are able to act on the incoming storm flows prior to their entry into the CW, such sediment build-up problems will be less of a problem. However, long term use of a CW for storm water remediation purposes will invariably require the operator to remove accumulated sediment since no sedimentation basin is perfect. Close monitoring and timely removal of the sedimentation build-up processes in both the sedimentation basin and CW are necessary for continued operation efficiency and reasonable lifetimes. The potential for sedimentation problems in the CW is highly dependent on the incorporation of a sedimentation structure prior to the CW, or lack thereof, and the suspended solids characteristic of incoming storm flow.

The fourth consideration named by the professionals above concerns the effects of artificial versus natural water level fluctuations on wetland plants and animals. Water level perturbations experienced by naturally occurring wetlands tend to be beneficial to wetland vegetation. Mitsch's article, described in the wetland modeling section above addresses this finding. Stagnant water conditions do not deliver needed nutrients such as phosphorous and nitrogen into the wetland plants. Flowing conditions provide nutrients at a constant rate, however it seems that there may be some difficulty in securing maximum concentrations of such nutrients under such conditions. Mitsch found that pulsing conditions allow adequate nutrient flow as well as maximum uptake time to enhance vegetation production in a forested wetland (Mitsch, 1988:128). It is therefore imperative that the CW operator fully understand the nutrient requirements as well as the optimum water level conditions of the chosen plant species to maintain desired productivity.

The fifth and final consensus consideration was possibly the most important, and one facet of this concern is the crux of this paper's research. Accumulation of any non-

degradable pollutant in the CW is of concern since the CW is a living ecosystem and not merely a inert filter that can be throw away when it becomes unusable. Pollutants such as nutrients, BOD, and sediments can usually be filtered and purified in a CW, however trace metals, though not entirely unaffected by CW processes, can accumulate and therefore a toxicity potential exists. Close monitoring of wetland conditions including water, soil, plant, and animal sampling for toxic accumulations of any such pollutant is important to continued long term CW operation and eventual clean-up cost avoidance.

Trace Metal Removal Optimization - L.E. Gadbois relates that the CW designer for storm water mitigation must evaluate the three different categories of pollutants, of which, trace metals can be found in all three:

1. Pollutants found in the settleable fraction are dependent on the wetland retention time which is obtained by slow water velocities which allow settling and subsequent decomposition.

2. Pollutants which cling to organic material and adhere to those binding sites provided by wetland vegetation and substrate.

3. Pollutants that are dissolved in the storm water volume. The CW must contain the storm flow long enough for pollutant degradation to take place which may make this type of pollutant the most difficult to consistently remove in reality (Gadbois, 1989:26).

Shutes and others have suggested five principles found to be effective in metal removal by CWs:

1. Avoid short circuiting, provide good horizontal sheet flow if possible.

2. Use gravel substrate which will allow for high hydraulic loadings and provide for adequate root growth.

3. Introduce storm water flow below ground if possible to maximize contaminant contact with substrate binding sites.

4. Monitoring of plants to ensure metal accumulation levels are not depressing filtration capacity and growth.

5. Harvest of plants that no longer are removing trace metals due to overloaded out capacity (hypothetical). Harvest of plants to renew growth and vigor to wetland productivity (more reasonable).(Morishi/Shutes, 1993:412-13)

These principles too must be considered in any CW design intended to receive AF storm water flows. The first principle can be realized by spreading the flow out along the width of CW, instead of introducing storm water from a single inflow pipe. Such spreading flow designs are shown in Figure 2.2 above. By diverting and breaking up the magnitude of the incoming storm flows, a sheet of water will be acted on by the CW instead of a channel of water which can easily create short detention time scenarios. Sheet flow slows the inflow more efficiently and allows the full width of the CW processes to act on the storm water pollutants.

The second principle above suggests that gravel be used in place of typical hydric soils found in naturally occurring wetlands. This principle goes hand in hand with the third suggestion of using subsurface inflow. Such artificial substrate should allow adequate subsurface flows without high channelization problems. Subsurface inflow allows the storm water pollutants to contact a maximum amount of soil adsorption sites which is paramount in removing dissolved metals. However, subsurface flows can create channels in typical wetland soils since the water flow is being forced through relatively small pore spaces inherent in clay and silt materials. These channels allow the water flow to quickly pass through the CW without being acted upon by the purification process. Gravel substrate has much larger pore spaces allowing uniform subsurface flows to be maintained. One concern with such artificial substrate material would be the ability of the chosen vegetation to produce necessary root growth in such conditions. This consideration must be evaluated if a gravel substrate is incorporated in CW design. The fourth principle involving CW monitoring and sampling was discussed under the storm water design considerations above. It is important that such evaluations are done at regular intervals to ensure CW viability.

The fifth and final recommendation may be the most controversial. The first part of this principle, postulates that since trace metals are accumulated in CW vegetation some maximum concentration of metal accumulation may be reached. Though the plant may not die, it will no longer continue to take up metals from the CW soil. In order to maintain plant uptake and removal of metals from the CW soil, it would seem reasonable that such vegetation would require harvesting upon reaching maximum accumulation levels. This theory is debatable since the majority of metals in CWs seem to be bound in the sediments with a small percentage incorporated into plant tissues. Thus, harvesting of plant biomass from the CW to effect metal removal seems unimportant in light metal accumulation locations and their respective magnitudes (Hammer/Faulkner, 1990:61). Harvesting of plants to effect continued growth and productivity, on the other hand, may have some merit, although this maintenance measure will be highly dependent on the type of vegetation chosen for a CW.

A Final Design Note - There are obviously many more considerations that must be analyzed by the prudent CW designer, however such coverage is beyond the scope of this paper. An excellent introduction to CW design for storm water mitigation is provided in the State of Maryland's "Guidelines for Constructing Wetland Storm Water Basins."

III. Preliminary CW Design Model

This chapter provides a partial description of the methodology that was used to investigate the findings and recommendations of the next chapter concerning the possibility of metal removal efficiency and accumulation in CWs used as storm water best management practices. The design of the hypothetical CW treatment system is discussed first to provide an understanding of the wetland to be modeled. The rest of the chapter consists of following the metal constituent in the storm water flow through the CW system as defined by the Stella II model. Although the actual model contains six different sectors which together describe the CW treatment system, only the metal sector is focused on here. Each of the six individual model sectors (hydrology, soil, plant biomass, microbial population, metal, and concentrations of interest) including mathematical equations, brief documentation, and pictorial representations are provided in Appendix B.

Hypothetical Wetland Design

In order to simulate a CW for storm water mitigation and pollutant removal (specifically trace metal removal), a hypothetical CW treatment system was designed. Parameters such as wetland and detention basin volumes and variables such as inflow and outflow rates must be known for a simulation to produce data of any significant value. This section takes the reader through basic considerations in designing a CW and associated detention basin. The following procedures are intended to be a starting point for a hypothetical model and should not be followed to the letter in designing an actual CW system. Specific locations will involve much more complex landscapes and hydraulic conditions than the hypothetical situation described here. Many assumptions have been made to facilitate the building of this model, yet remain within the scope of this project's purpose. The reader must fully understand the assumptions inherent in this

hypothetical design and judge for themselves whether or not such assumptions are applicable to their own scenario.

Setting - The CW design is planned for a hypothetical Air Force base located near Atlanta, Georgia. This location has been chosen due to its temperate climate and the fact that it conditions are closely related to an actual Air Force installation, Warner Robins AFB, located in Macon, Georgia. Weather statistics for the Atlanta area are given in the following table (Hoffman, 1989:224):

Table 3.1

Monthly Normal Temperature* and Precipitation for Atlanta, GA (1951-1980)

Month	Temperature (°F)	Precipitation (inches)
January	42	4.9
February	45	4.4
March	53	5.9
April	62	4.4
May	69	4.0
June	76	3.4
July	79	4.7
August	78	3.4
September	73	3.2
October	62	2.5
November	52	3.4
December	45	4.2

*Normal Temperature is the product of all daily high temperatures for the month and daily low temperatures for the month (averages). These two averages are then added and divided by two to produce a monthly mean temperature or normal temperature.

Average annual rainfall is 48.61 inches. The hypothetical airfield which produces the storm water is assumed to have primarily concrete and asphalt pavements with a total area of 50 hectares (100 acres). Space for the CW is not restricted by property or construction constraints.

Average daily inflow was calculated to be approximately 1534.4 cubic meters per day which was derived from the Rational Equation. This equation provides a relatively simple method of computing the rainfall-runoff relationship. It is used to predict peak runoff rates from data on the rainfall intensity and a knowledge of land use in the

drainage basin. The rational method is of greatest validity when used in analysis of small drainage basins of 200 acres (100 hectares) or less. (This assumption is valid for calculations of storm water runoff on airfield pavements and small urban areas typically found on Air Force bases and especially airfields). The Rational Equation is:

$$Q = .0028\,(C\,I\,A)$$

where

Q is the peak runoff rate (cubic meters per second)

I is the average rainfall intensity (millimeters per hour)

A is the drainage area (hectares, 1 hectare = 100 ares = 10,000 m^2)

C is the runoff coefficient from the table listed in Appendix A

The Rational Equation assumes that the rainfall event lasts long enough for the maximum discharge of the drainage basin to occur. In order for such a simple relationship to hold, the rate of infiltration must also be constant during the storm (Fetter, 1988:49).

The "C" value presented above represents the watershed surface characteristic. This value was assumed to be very high (0.9 out of a maximum of 1.0) since runoff at typical AF bases are assumed to be from pavement sources. The hypothetical CW design assumes a drainage area of 50 hectares or 100 acres of asphalt and concrete pavement justifying a high "C" value which is used throughout each simulation. Paved areas typically have a high value (all or almost all runoff is entering the storm water rate versus filtering into the ground) while vegetated areas are usually lower. Runoff characteristics that do not warrant such high C values at specific locations should be modified according to the tabular values found in Appendix A (Fetter, 1988:50)

Rainfall intensity was considered to be a constant inflow to start the model at an initial equilibrium condition, however other simulations utilized varying storm inflow and storm durations. This variance in hydrologic inflows is not greatly important, since the period of concern (years) is not greatly affected with daily perturbations in hydrologic

conditions and therefore a constant average inflow was the primary inflow. If the hydrologic function of the wetland is more important for design considerations the model can be adapted to have a completely varying storm frequency, intensity, and duration. Storm frequency and intensity factors for Atlanta, GA would be 3.5 days and 0.1409 mm/hour respectively.

This equation, as noted previously, calculates peak storm flow values and thus the value of 1534.4 cubic meters per day will be an overestimate of actual flow conditions for a watershed area of this size and climate.

Detention Pond Design - Much literature is currently available on the subject of detention basin design for storm water mitigation since detention ponds are relatively simple and cheaply built holding ponds for storm water surge flows. They have long been used for flood protection to retard runoff and reduce flow rates, thereby mitigating downstream damage. However, the primary purpose for the detention pond in this scenario is to reduce the amount of suspended solids entering the CW. In order to accomplish this task, the storm water characteristics must be known or approximated. The settling velocities of the suspended solids in the storm water dictate the necessary detention time for them to be removed from solution. Whipple and Randall point out that a mean detention time of about 18 hours is adequate to settle about 60 % of total suspended solids, leads, and hydrocarbons and 45 % of the total BOD, copper, and phosphates from urban storm runoff (Akan, 1992:381). With this consideration in mind, it might seem desirable to design detention basins to retain storm flows as long as possible to remove the maximum amount of suspended solids. However this is not usually possible for two reasons. The first limitation concerns land availability and money. The second limitation is associated with stagnant bodies of water that can lead to unwanted conditions of mosquito production. The Florida Administrative Code requires that a detention basin empty within 72 hours after a storm event. The Delaware and

Raritan Canal Commission requires that 90 % of the runoff be evacuated within 36 hours, or within 18 hours for residential areas (Akan, 1992:381). So while it is desirable to contain storm water flows to reduce pollutants, most communities limit the amount of time such flows can be retained.

To maximize sedimentation and yet retain storm flows for a minimum duration, a time constant of 1.54 days is utilized for the detention pond. This value represents a detention basin whose average water flow is retained for approximately one and a half days. (It is assumed that the system designer is capable of designing a detention basin that will discharge its flow in accordance with this time constant value by way of various design procedures and flow slowing measures.) This time constant allows 15 % of the total volume to remain in storage after 3 days or 72 hours. Using the average daily inflow rate of 1534.4 cubic meters per day and an outflow rate based on a time constant of 1.54 days the required detention pond volume can be calculated as follows:

$$\textit{Inflow} = \textit{Outflow (at equilibrium)}$$

therefore

$$1534.4 = \frac{\text{Detention Pond Volume}}{1.54}$$

$$\text{Detention Pond Volume} = 1.54(1534.4) = 2360 \text{ m}^3$$

A safety factor of two was used to account for variability in storm flows and the reduction of volume due to sediment accumulation in the detention pond. A square area of 50 meters on a side with a 2 meter depth was assumed to be adequate for the detention basin, providing a volume of 5000 cubic meters.

Constructed Wetland Design - Unlike the detention pond whose design is fairly simple, a CW requires much greater effort to provide adequate water treatment efficiencies. The detention pond described above has no vegetation and a typically smaller microbial population than a CW. It has no reason for such complications since its primary function is to provide sedimentation which it can accomplish quite effectively

without such amenities. The CW, however, must deal almost exclusively with pollutants with settling velocities on the order of 10^{-6} m/sec. In order to settle out, precipitate, or adsorb such small particles, longer detention times and large numbers of adsorptive sites must be available in the CW. To accomplish this, a CW employs plant and microbial populations as well as a large amount of saturated soil. Plants found in this hypothetical CW consist of 50 % cattails (Typha latifolia) and 50 % common reed (Phragmites australus). These two species typically do well when planted in mildly polluted waters and can often be found in CWs used to treat municipal wastewater (Sediment and Stormwater Division, 1991:99-101) The water, soil, and plant type define the category of wetland which in this case is best described as an emergent freshwater marsh.

CWs are further divided into free water systems (FWS) or subsurface flow (SF) systems. This CW falls into the first category, resembling a natural marsh, having a soil bottom, emergent vegetation, and a water surface exposed to the atmosphere (Reed, 1992:776) Most of the CW's storage capacity is below ground. The CW soil in this scenario is assumed to have a porosity of 40 %. The CW water level (that is the level of water above the saturated soil) is only 0.2 meters while saturated soil makes up the remaining 1.8 meters of the CW depth. This scenario creates a large water storage capacity as well as a large number of adsorptive sites since the water entering the system is assumed well mixed within both the detention pond and CW. Since water entering both volumes is completely mixed within each total volume it is also assumed that water entering the CW filters through the saturated soil at some point prior to discharge.

The receiving watershed area is assumed to incorporate 50 hectares. Design literature on sizing a CW suggests that no less than 1-3 % of the total watershed area be utilized for a CW. Similar literature sources relate that designs incorporating a minimum of 3:1 and 5:1 length to width ratios are required to effect desired efficiencies (Stockdale, 1991:19). CWs with higher length to width ratios should theoretically provide even

greater removal rates if all other factors are equally maintained. The initial CW for this project has a length to width ratio of almost 9:1 which meets the above suggestion and may fit in well with most airfield siting plans which may already discharge untreated storm water to some type of ditch with a high length to width ratio.

CW volume for this project was determined by simulating the CW inflow described previously as well as the CW outflow through a weir equation. The resulting accumulation of water in the model's hydrologic sector was assumed to be the initial volume required by the CW to retain the storm flow. The model showed a water accumulation of approximately 20,000 cubic meters which became the CW design capacity. The CW size adequate to contain this volume was determined by calculating both above and below ground capacities that would be required. Based on the porosity and water level characteristics of a fresh-water marsh, the size of CW having the necessary capacity was calculated to be 21,750 square meters or 435 meters by 50 meters.

Water stored in CW soil = 1.8 m (depth) $\times$ 435 m (length) $\times$ 50 m (width) $\times$ .4 (porosity)

$= 15{,}660 \text{ m}^3$

Water stored above CW soil = 0.2 m (depth) $\times$ 435 m (length) $\times$ 50 m (width)

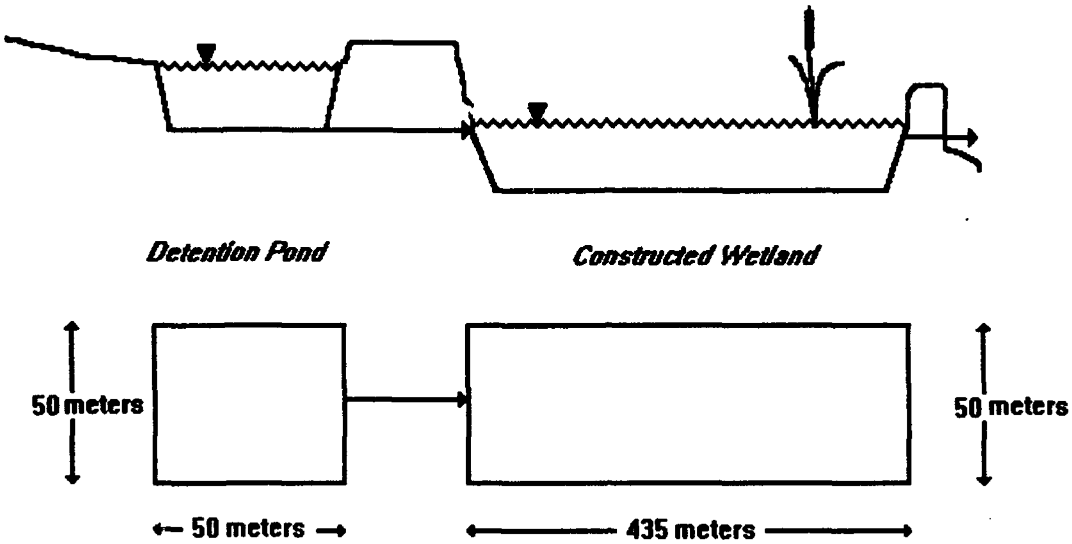
$= 4{,}350 \text{ m}^3$

Total CW Volume = $15{,}660 + 4{,}350 = 20{,}010 \text{ m}^3$

The dimensions of both the detention pond and CW are shown below along with a general schematic of the total treatment system.

Figure 3.1

General Schematic of the Constructed Wetland System



CW Metal Sector

Metals can accumulate in five different locations in the CW system although there are only four accumulation stocks represented in the Stella II model sector. The four stocks include the detention pond water, detention pond sediment, CW water, and CW soil. The fifth location trace metals can accumulate is in the CW's plant biomass, however this accumulation is represented only as a concentration not as a material stock. The following discussion follows the metals inherent in AF storm water through the Stella II model including their generation, accumulation, and exit from the CW. All flow rates in the metal sector have units of milligrams per day and stocks accumulate metals in milligrams. Auxiliary variables in this sector have various units which are listed under their respective headings. A pictorial representation of this sector is shown in Appendix B.

Metal Introduction

The metal concentration entering this CW system model is assumed to come entirely from that fraction inherent in AF storm water. Other hydrologic flows entering a wetland system could potentially be responsible for additional metal inputs. Hydrologic flows such as rain water, tertiary sewage treatment, and ground water discharges can all contribute metals in various proportions specific to site conditions. These alternate flows, however, do not typically contribute as wide a variety or as great a magnitude of metals as can be found in storm water flows. In order to decrease the complexity of model building as well as focus on the effects of storm water in a CW, potential metal contributions from other than storm water sources were omitted. Actual CW system design should evaluate potential pollutants from all hydrologic flows entering the CW. These flows can then be added in the necessary sectors to provide a more realistic picture of a specific site scenario.

AF storm water concentrations for various metals found in Table 2.4 show a fairly wide variety depending on type of metal as well as the sampling location (not shown). These concentrations were assumed to be those found after the respective AF installation had instituted pollution prevention measures to limit metals from entering their storm water flows and thus a CW system as a best management practice is to be evaluated to further reduce these metal concentrations. A metal concentration of 50 µg/L was used to initialize the CW model, however a range of values were eventually tested and their outcomes are listed in the next chapter. The selected concentration of metals was then multiplied by the calculated storm water hydrologic flow rate to determine a milligram per day metal input value which flowed into the detention pond.

Metal in Detention Pond Water

Once combined with the storm water hydrologic flow and transported to the detention pond, metals in the water column is assumed to follow one of two paths. The first path consists of the metal concentration flowing through to the CW, while the second path is for the metal in the detention pond to become part of the detention pond soil through primary sedimentation. These pathways are depicted in the figure below. Accumulations of metal are shown in bold print while flows are shown in italics.

Figure 3.2
Metal Pathways from the Detention Pond Water

Metal in Detention Pond Water — *CW Hydrologic Inflow Rate* → **Metal in CW Water**

Primary Sedimentation Rate

Detention Pond Sediment

The metal concentration in the detention pond can be characterized by both a dissolved fraction as well as a particulate fraction. The metal concentration entering the CW system in this case was assumed to be equally divided between dissolved and particulate portions. The metals dissolved in the storm water were assumed to be unaffected by the detention pond sedimentation process due to the lack of adsorptive sites (saturated soil filtration and plant biomass) for metals to attach to. In an actual detention pond, some dissolved metals would precipitate out of solution or be adsorbed by the bottom sediment depending on metal species and site specific characteristics such as pH, however, detention ponds alone are not typically employed to remove metals from storm water. The dissolved metal fraction then passed directly into the CW as determined by its hydrologic inflow rate. This resultant metal inflow rate then represents that fraction of metals associated with the unsettleable soil fraction and the settleable sediment that is not

removed by the detention pond due to its less than perfect efficiency which continues on to the wetland water volume. It also includes that fraction of metals dissolved in solution and not associated with any particulate matter.

The metals in particle form, however, were affected by the sedimentation provided by the detention pond. A concentration for metals attached to the suspended soil in the detention pond water was first determined outside the metal sector. This concentration was then multiplied by the primary sedimentation rate affecting the soil suspended in the detention pond water. This provided a rate at which particulate metals were removed from solution and fell to the detention pond floor. Once on the detention pond floor, the metal particulate matter was assumed to accumulate until mechanically removed by the system operator. No resuspension of metals in the detention pond sediment was considered.

Metal In Detention Pond Sediment

If metal particles in the detention pond water are affected by the primary sedimentation rate and fall out of the water column, they accumulate along with larger soil particulate matter on the floor of the detention basin. Since there is assumed t › be no resuspension of soil or metal particulate into the detention pond water by way of adequate detention pond design, no natural outlet for metals exists from this accumulation point. However sediment and soil cannot be allowed to build up to excessive levels (1 meter or greater) in the detention pond since its presence reduces the detention pond volume as well as makes resuspension a possibility that must be considered significant. Thus it is assumed that the CW operator will remove sediment from the detention pond on a regular interval as part of a maintenance plan. As soil is removed from the detention pond according to the sediment removal goal, so too is the metal that has fallen out of suspension on the detention pond floor. This rate of removal is calculated by determining

the concentration of metals in the detention pond sediment and multiplying it by the expected soil removal rate. The soil and metals that are removed are assumed to be properly disposed of in a sanitary landfill as long as the metal concentration is not greater than the associated sewage sludge standards allow.

Metal In CW Water

Metal in dissolved form as well as particulate form which was small enough to be unaffected by the primary sedimentation in the detention pond pass on to the CW water volume. The CW provides excellent filtration capabilities through its plant biomass density above ground as well as its saturated soil matrix below ground. The CW also provides numerous adsorptive sites for metals to attach to and remain in the wetland. These removal processes offered by the CW cause the majority of metals in the water column, whether in particulate or dissolved phases, to make the CW a "sink" for metals. Once part of the CW water column, the metal can undergo one of three removal mechanisms. The possible pathways are shown below in Figure 3.3.

Figure 3.3
Pathways of Metals from the CW Water Column

Metal Concentration in CW Water —— *CW Hydrologic Outflow Rate* —— **Metal Concentration in CW Outflow**

Precipitation \ Adsorption Rate | *Secondary Sedimentation Rate*

Metal Concentration in CW Soil

As detention pond water becomes part of the CW water volume, its channelized surface flow is transformed into a homogeneous sheet flow due to the plant biomass in the CW. This slowing of flow in the CW causes the metal particulates in solution to see

longer detention times which allow for greater sedimentation of smaller particles not affected in the detention pond. Similar to the primary sedimentation rate discussed under the detention pond water heading above, the secondary sedimentation rate is also tied directly to sedimentation rate of soil particulate matter and does not account for any precipitation of metals from the CW water column. Thus a concentration for metal adsorbed to suspended soil in the CW is calculated outside the metal sector and then multiplied by the secondary sedimentation rate associated with the soil sector. The resulting flow represents the rate at which particulate metals will fall out of suspension and accumulate in the CW soil.

The fraction of metal not affected by the secondary sedimentation rate due to its particle size or dissolved state eventually flows through the saturated soil matrix in the CW. In this matrix of soil, roots, and plant litter, a multitude of adsorptive sites are available to collect the metals in solution. This layer of soil also offers reduced soil and favorable pH conditions for precipitation of dissolved metals to occur. Different metals have different precipitation and adsorption rates and therefore it is imperative that some knowledge of typical precipitation and adsorption rates are known for this rate to be specific and realistic. The rate described here is based on an average removal efficiency fraction which is then directly affected by the pH, water temperature, and the microbial population which has the capacity to utilize certain metals as well as reduce certain metal species to less toxic forms. A CW pH value of less than 7.0 will tend to keep metals in solution, while water with a pH value greater than 7.0 will have a greater tendency to lose its metal concentration to the soil stock. Higher water temperatures tend to cause greater precipitation of metals out of the water column and lower temperatures have an opposite effect. Together these variables are combined to create a fraction which is multiplied by the metals in the water column to produce a rate at which metals are expected to be adsorbed and/or precipitate out of solution into the CW soil matrix.

The metal fraction not affected by secondary sedimentation, precipitation, or adsorption removal processes become part of the CW outflow. This outflow rate represents the rate at which metals in the CW water volume are discharged along with the CW hydrology outflow. The rate at which metals exit the CW show the overall removal rate of metals entering the CW system since it is this outflow concentration which will be measured for compliance with regulatory agencies. This flow rate assumes that the metal concentration in the water volume is well mixed throughout the CW. This assumption may be conservative, since water exits most CWs as far away as possible from its point of origin, thereby allowing the full length of the CW processes to affect the metal concentration. This would lead one to believe that water near the CW inflow would typically have more metals than water near the CW outfall. The model however does not account for this gradual metal concentration degradation since all pollutants in the CW volume are assumed to be homogenous throughout.

Metal In Wetland Soil

Metals entering the CW soil matrix tend to primarily accumulate there until mechanical removal is performed by the CW operator, however two possible outlets are available. These possible outflows are presented in Figure 3.4 below.

Figure 3.4
Metal Pathways from the CW Soil

Metal in CW Soil —— *Resuspension of Metals* —— **Metal in CW Water**

Plant Metal Uptake Rate

Metal in Plant Biomass

Turbulent water flows through the CW can cause soil and metals to become resuspended into the CW water volume, thus negating the anticipated metal removal effectiveness of the CW. Typically the amount of metal that is resuspended due to turbulent water flow is considered to be small if the CW designer has successfully planned for surging storm flows. The resuspension rate of metals is directly dependent on the soil resuspension rate and the metal concentration in the wetland soil. Together these factors create an outflow rate that represents the undesirable possibility of reintroduction of metals back into the CW water column. If resuspension of metals takes place, sedimentation, adsorption, or CW outflow associated with the CW water column discussed above become potential pathways again.

If the metals in the CW soil remain there and accumulate instead of returning to the CW water column, they can also be affected by plant uptake and subsequent removal from the CW. This outflow rate represents the removal of metals accumulated in the plant biomass as the plants themselves are removed from the CW (and properly disposed of) through a regular harvesting rate associated with the plant biomass sector. This removal rate is controlled by the harvest outflow rate and the metal concentration in harvestable plant biomass. This distinction of harvestable versus, non-harvestable plant biomass is important since most of the metal concentration in the CW's plant biomass tends to accumulate in the roots and rhizome parts of individual plants rather than the outer leaf sections. This condition greatly reduces the potential for metals to be removed by harvest from the CW since harvests are assumed to remove only outer leaves and stems of the CW biomass. Root and rhizome materials cannot be removed regularly due to the potential for resuspension of sediment into the CW water column.

Metal In Plant Biomass

Although this accumulation point is represented as a variable and not a stock, it does represent another important location metals can accumulate in the CW system. In the June 93 issue of Environmental Toxicology and Chemistry, Dixon and Florian, Jr. relate two possible ways plant and animal uptake rates can be modeled. The first is to develop expressions for biomass dynamics and contaminant mass balance. The concentration then is simply the ratio of contaminant to biomass. The second approach is to develop a single expression for concentration (Dixon, 1993:2288) It is their second suggested method that is used in this model. Plant uptake rates of trace metals are indeed controlled by numerous factors; including type of plant species, the trace metal in question, the age of the plant, and the concentration of metal in the soil. However such detail is not the focus of this research. Instead a simpler relationship is utilized to calculate the concentration of metals in the CW biomass. The single expression method suggested by Dixon and Florian can be equated to a partition coefficient which relates the concentration of metals in the soil to that in the plant biomass. Instead of gradual accumulation of metal over time, a partition coefficient assumes that the plant biomass concentration is always at equilibrium and thus its concentration is simply a percent of the concentration found in the sediment. Although this assumption seems simplistic on a micro or day to day scale, it becomes much more realistic when the time scale of interest is much greater than the time a plant's metal concentration takes to get to equilibrium. This is the case with the CW model created for this project. According to Shutes and others, eight week experimental metal dosing of Typha latifolia and Juncus effusus plants showed similar concentrations of copper, lead, and zinc in leaves and stems when compared to urban sites in existence for years (Morishi/Shutes, 1993:412). Partition coefficients have also been expressed in non-wetland experiments to express realized metal concentrations in lettuce and chard plants grown in sewage sludge over a growing

season. Such experiments show that metal concentrations in such plants became similar to those found in the substrate material within a growing season (Merrymon, 1993:36). Therefore, it would seem reasonable to forego factoring in many unknown variables to determine the metal concentration present in the plant biomass, when a simpler soil concentration relationship is applicable. The following table shows the resulting ratios found by Shutes and others in their metal dosing experiments (Morishi/Shutes, 1993:412):

Table 3.2
Metal Concentration Ratios of Sediment, Root, and Rhizome to Typha Leaf

Trace Metal	Sediment Fraction	Root Fraction	Rhizome Fraction	Leaf Fraction
Cadmium	3.7	1.8	1.1	1
Copper	1.5	2.8	1.5	1
Lead	44.8	5.1	1.7	1
Zinc	21.8	4.6	1.2	1

Based on this evidence of plant uptake rates of metal from the soil and the assumption that the plant concentrations are always at equilibrium values, the concentration of metal in the plant biomass is simply calculated by multiplying the soil concentration by an appropriate fraction associated with a specific metal and plant type. This concentration then affects both the metal removal rate through harvesting of CW biomass as well as the metal return rate through decomposition of plants formerly containing metals concentrations.

The metal removal rate was described in the last section as removal of metals from the CW soil, however since the metals in plant biomass is a concentration rather than an accumulation return of metals from the plant biomass has not yet been mentioned. This outflow of metals from the plant biomass metal concentration represents the rate at which dead plants remaining in the CW decompose and release their stored metals. It is dependent on the concentration of metals in the plant biomass and the rate at which plant decomposition takes place due to microbial activity. Plants do tend to accumulate metals

as seen in the discussion above, however unlike other nutrients such as nitrogen and phosphorous, the metals tend to remain unchanged. Thus their removal from the soil to the plant biomass is merely a temporary storage before they are either harvested or return to the CW soil.

IV. Results and Analysis

This chapter consists of a presentation of data and corresponding analysis resulting from the Stella II model that was described in Chapter III. The initial data is first compared to actual field data from various sources to ensure reasonable accuracy with reality. Additional data, created by varying both the expected storm water metal concentrations and the size of the CW, is then presented. These two parameter variations provide a range of results covering a wide range of possible CW scenarios designed to mitigate storm water flows. The resultant data is then analyzed to evaluate both the effectiveness of metal removal, the expected lifetimes of such CWs, and the possibility of metal accumulation and potential toxicity. Many of the graphs associated with the simulations in this chapter are not shown, however each section has a single graphical representation to give a general idea of the simulation curve. Results for all model variations are contained in the tables associated with their respective CW sizes.

Model Validation

In order to ensure a reasonable sense of accuracy, some model validation and comparison to field results is justified. The following paragraphs provide a general insight into the accuracy the model provides by presenting important stock values, removal rates, and resultant concentrations using the constant input data described in Chapter III.

Stocks

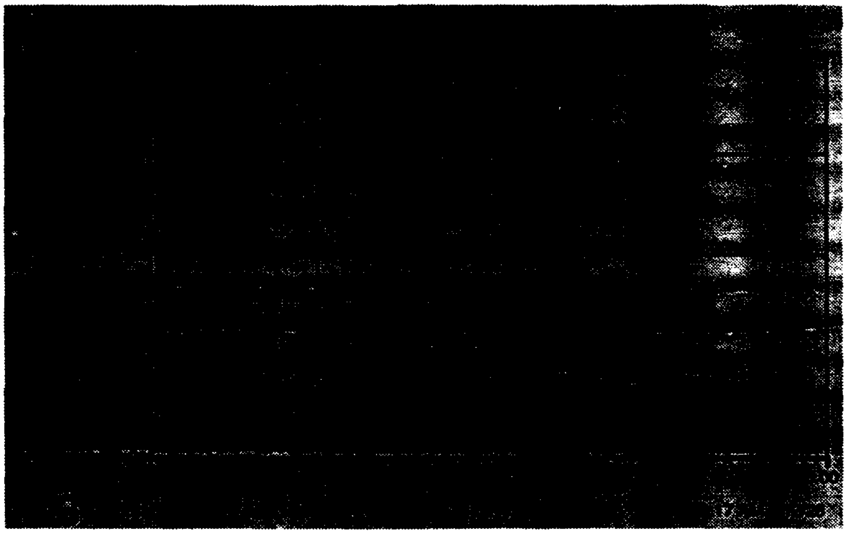
Detention Pond Volume - The detention pond volume was directly dependent on the constant inflow and outflow of water to its stock, therefore its volume quickly came to an equilibrium value of 2358.73 m^3. This value is only half the actual volume of the detention pond, however the inflow used in each simulation was an expected storm water

value and greater inflows could be expected periodically. Since much of the primary sedimentation is accomplished through the detention pond, it is imperative that its size be adequate to slow the storm volumes prior to reaching the CW. The detention pond provides a cheap and highly efficient means of preserving CW lifetimes and efficiency, and it would seem prudent in designing such a treatment system to adhere to the conservative adage of "better to be safe than sorry."

Constructed Wetland Volume - The CW volume stock depends on the detention pond outflow, its head dependent outflow, and the depth change rate which accounted for the build-up of sediment (and resulting displacement of water) in the CW. The CW volume stayed close to its initial starting value of 20,000 m^3, however the sediment not removed by the detention pond began to decrease the CW volume almost immediately. Within one year, the CW volume was reduced by almost 1500 m^3! The accumulation of sediment in the CW was not initially expected to have such an impact on CW volume and the model was modified in order to keep within the focus of the intended project. The hydrology sector of the model was modified by removing the depth change rate and its corresponding effect. It is important to note, however, that some removal of sediment from the CW will probably be required regardless of detention pond efficiency if a CW receiving storm water is to continue operating efficiently. Thus, a CW design that allows for a sediment removal capacity is recommended. The removal of the depth change rate variable now assumed that the CW had the ability to expand outside its initial borders and the weir height affecting CW outflow was simply raised to accommodate this increasing displacement of water. Such an assumption, could be valid in some field situations where CW boundaries are not strictly defined, however it was assumed valid for this ideal scenario. After this modification, the CW volume quickly came to an equilibrium value of 20,204.44 m^3. As discussed in Chapter III, this volume was determined based on multiple iterations of the hydrology sector using the constant water inflows. CWs come

in all shapes and sizes and this CW design is just one possible variation. The following Stella II graph shows both the detention pond and CW year-long elapsed volume histories as they come to their respective equilibrium values.

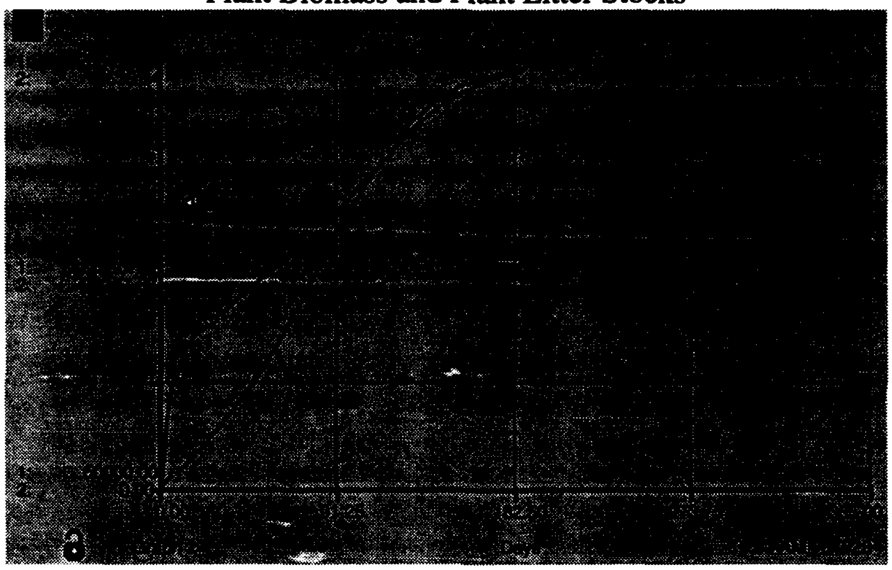
Figure 4.1
Detention Pond and CW Volumes



Plant Biomass - The plant biomass stock followed a typical S-shaped growth curve and reached an equilibrium value of 209,014.72 kilograms. This value was based on a maximum standing crop of 10 kilograms/m^2. This value is not typically very comparable to naturally occurring or CWs in the field since net primary production rather than standing crop is usually the measure of plant biomass. Plant litter followed a similar path to that of the plant biomass initially, however when the microbial population was low, a much steeper curve resulted. As the microbial population continued to expand and reduce the plant litter stock, an equilibrium value was reached at approximately one-tenth the living plant biomass stock. Plant litter values are very unpredictable in nature since degradation values for return of nutrients and metals within decaying plants varies with the type of wetland studied, field conditions, and type of plant species. This variance was experienced by Armando A. de la Cruz who studied decomposition rates in

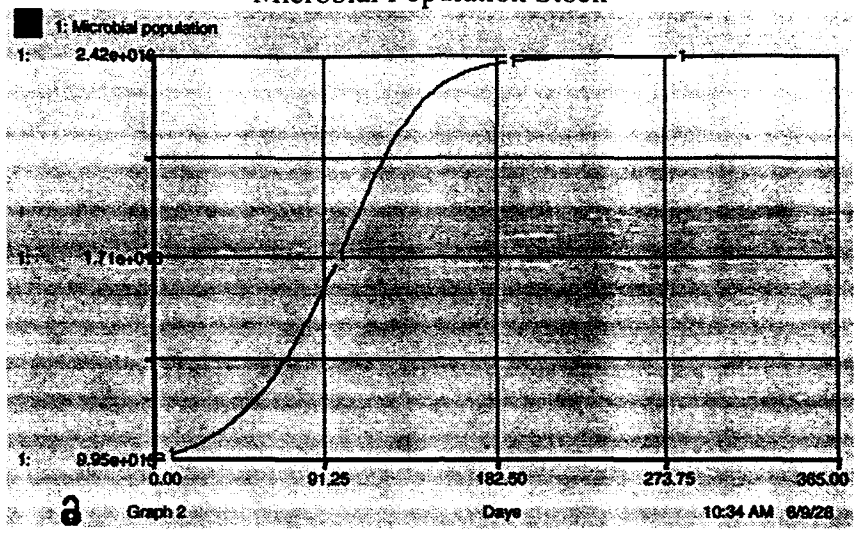
30 species of fresh water and 11 species of salt water wetland plants. Decomposition rates determined by the litter bag technique vary in fresh water species from 60 to 80 percent breakdown of material over a 90-day period and from 40 to 100 percent for a one-year period (Greeson/de la Cruz, 1978:162). The following Stella II graph represents the initial growth and equilibrium value attained by both the plant biomass and litter stocks for a period of one year in the hypothetical CW.

Figure 4.2
Plant Biomass and Plant Litter Stocks



Microbial Population - Similar to the plant biomass stock result described above, the microbial population followed a S-shaped growth curve and reached an equilibrium value of 2.42×10^{16} colony forming units. This value was based on a maximum value of 2.85×10^{6} colony forming units per gram of soil for 50 % cattail and 50 % reed communities described by Hatano and others (Morishi/Hatano, 1993:543). Figure 4.3 shows the growth curve of the microbial population in the hypothetical CW over a one year period. Microbial population stock units are number of colony forming units in the CW.

Figure 4.3
Microbial Population Stock



Removal Rates

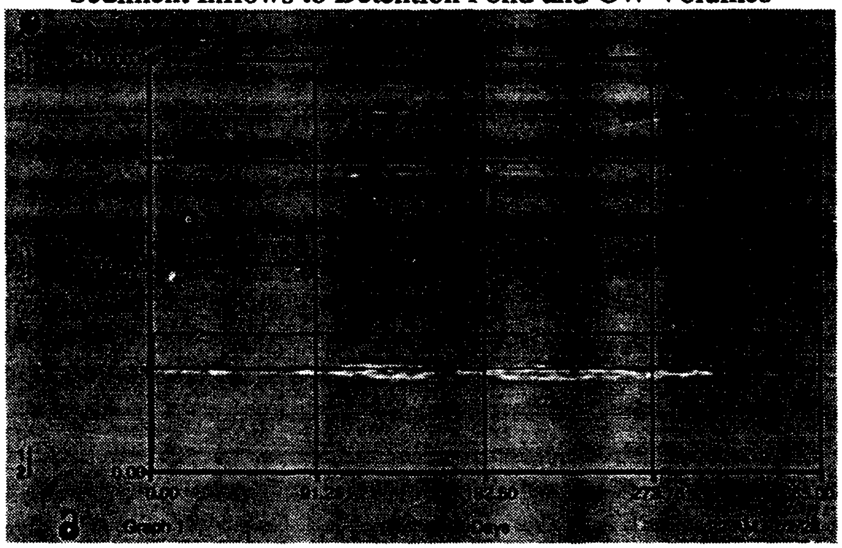
Primary Sedimentation - Removal of suspended sediment from the water column by a sedimentation pond is vital to the longevity of any CW treatment system. Such removal was simulated in this model by the primary sedimentation rate outflow. The inflow of sediment into the detention pond stock was assumed constant since it was directly tied to the constant storm water rate. Its value started and remained at 109,050.04 kilograms of sediment per day. The sediment remaining in the water exiting the detention pond volume defined that sediment that would in turn effect the CW and described the detention pond removal efficiency. The value of the detention pond sediment outflow quickly reached an equilibrium value of 35,441.26 kilograms per day. Thus the detention pond sediment removal efficiency can be described by the following equation:

$$\frac{109050.04 - 35441.26}{109050.04} = 0.675 \text{ or } 67.5\ \%$$

This removal efficiency is not unlike those experienced in actual detention ponds, however this value is highly dependent on the particle size distribution of the incoming sediment. Whipple and Randall expect 60 % of total suspended solids in storm water

volumes to be removed by detention times of 18 hours (Akan, 1992:381). This 18 hour requirement was met and exceeded in this hypothetical detention pond design, and thus the higher removal rate should be expected and is probably conservative for an expected average detention time of 1.54 days (37 hours). Figure 4.4 shows the soil inflow rate entering the detention pond and the sediment flow entering the CW over a one year period of hypothetical system operation.

Figure 4.4
Sediment Inflows to Detention Pond and CW Volumes



Secondary Sedimentation - Those particles of soil and sediment that were not affected by the detention pond then proceeded to the CW and were affected by the removal rate entitled secondary sedimentation. This removal rate attempted to define the sedimentation processes found in a CW. Its constant inflow of soil was 35,441.26 kilograms per day or the detention pond outflow rate. The CW outflow rate of sediment was described by the soil concentration in the CW water which was tied directly to the hydrologic CW outflow rate. CW sediment outflow came to an equilibrium value of approximately 25,000 kilograms per day. Thus, the sediment removal efficiency of the CW can be described by the following equation:

$$\frac{35441.26-25000}{35441.26} = 0.2946 \text{ or } 29.46\ \%$$

Such a low value (compared to the detention pond removal efficiency) may be conservative due the modeling procedure described by the "soil loss rate(outflow)" equation of the soil sector. R. L. Knight's survey found an average sedimentation efficiency of 68.8 % for wetland treatment systems (whether natural or constructed). This value is much greater than the individual CW model value of 29.5 %, however when the entire model system of both CW and detention pond are combined, the following efficiency is calculated:

$$\frac{109050.04 - 25000}{109050.04} = 0.7707 \text{ or } 77.07\ \%$$

This value is very comparable to the value provided in the Knight article and thus the model's simulation of the entire system sedimentation removal efficiency is not unreasonable. Figure 4.5 shows the inflowing CW sediment rate and its counterpart outflow rate. Figure 4.6 presents the initial DP sediment inflow rate as well as the final CW outflow rate.

Figure 4.5
Sediment Inflow to CW and CW Outflow Rates

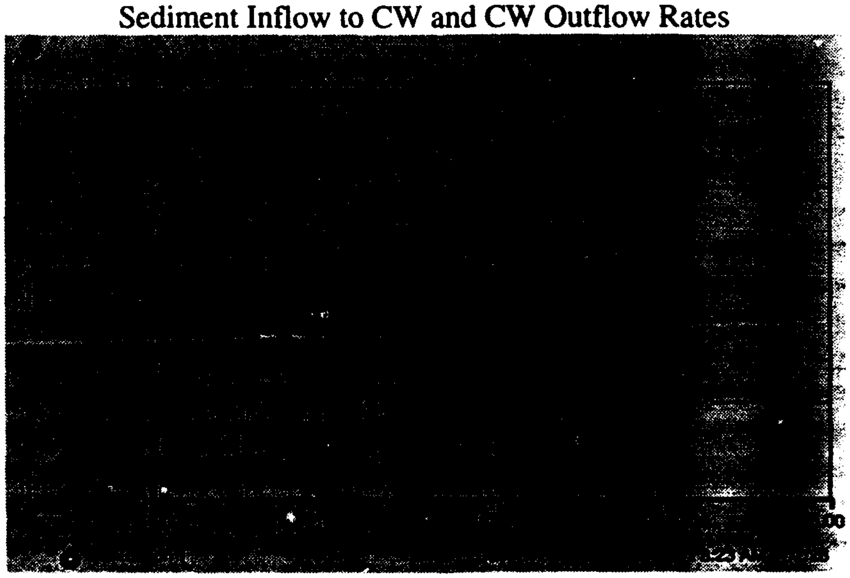
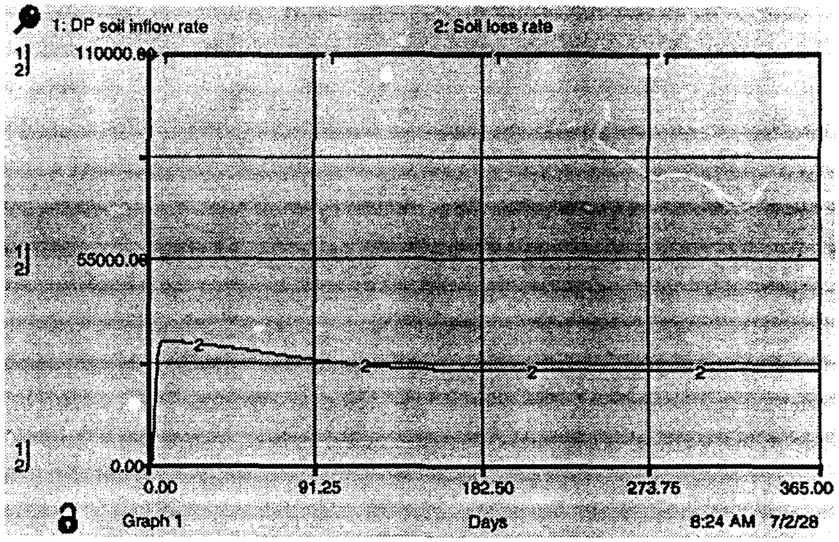


Figure 4.6
Sediment Inflow to Detention Pond and CW Outflow Rates



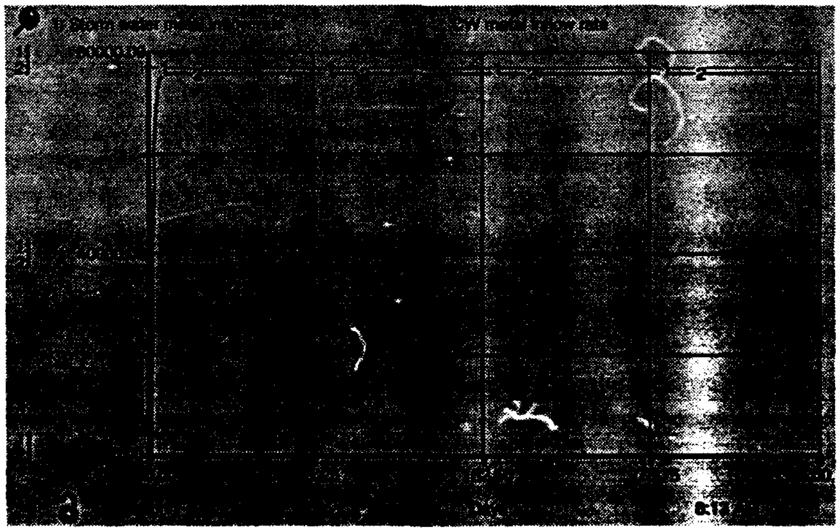
Detention Pond Metal Removal - Metal concentrations in this simulation were assumed to be present in both the particulate and dissolved forms. The fractions of each form were assumed to be evenly distributed. That percentage of metals attached to particulate matter was assumed to be affected by removal processes that affected the particulate matter. That percentage of metals in solution were assumed to be affected only by precipitation and adsorption removal processes found in the CW system. The initial concentration of metals flowing into the detention pond was defined by a constant metal concentration (50 ppb) as well as a constant storm water inflow rate. These two constant components created a metal inflow rate of 76,720.16 mg/day. After the sedimentation process had its chance to reduce the metal fraction attached to particulate matter, the metal outflow from the detention pond was still 75,976.59 mg/day. Thus, the removal efficiency of metals by the detention pond was described by the following equation:

$$\frac{76720.16 - 75976.59}{76720.16} = 0.0097 \text{ or } 0.969\ \%$$

This value shows that the detention pond is doing little to remove metals from the water column with less than one percent of the total metal concentration affected. Mesuere and

Fish found that such negligible influence by the detention pond may be unreasonable for certain metal species such as copper and lead (Mesuere, 1989:136). However, other metals such as cadmium and some species of copper can be found primarily in the dissolved state (Hvitved-Jacobsen, 1987:140). Since such variability in detention pond removal efficiencies on trace metal concentrations exist, a conservative approach may be in order. If a conservative approach is taken and the metal in question is assumed to have a high affinity for the dissolved state, very little of its initial concentration would be expected to be removed by the mere sedimentation provided by the detention pond. Therefore, although conservative, a 1 % sedimentation removal rate of trace metals by the detention pond may be appropriate. Different metal species may dictate greater effects of the detention pond on metal removal from the water column. Figure 4.7 shows the initial metal inflow rate into the detention pond and the resultant inflow rate of metal to the CW.

Figure 4.7
Metal Inflow Rates to Detention Pond and CW Volumes



Constructed Wetland Metal Removal - The metal concentrations reaching the CW were those not affected by the sedimentation in the detention pond, much of which was assumed to be in the dissolved state. This metal inflow rate was 75976.59 mg/day. The

metal outflow rate exhibited by the CW was determined by the metal concentration in the water column and the hydrologic outflow rate. Its value was initially 24828.17 mg/day, however as the plant and microbial populations became active this value was almost cut in half. In approximately 9 months of operation, the CW model showed a minimum metal outflow rate of approximately 14,500 mg/day. This outflow rate of metals gradually increased as additional metals were added to the CW soil as well as metal return through plant death became apparent. However, these additional increases were very minor and their effect seemed negligible on overall system performance. Using the 14,500 mg/day value, the CW metal removal efficiency is calculated as follows:

$$\frac{75976.59-14500}{75976.59} = 0.809 \text{ or } 80.9\ \%$$

Using the maximum value of 24,828.17 mg/day found at CW start-up, a removal efficiency of 67.3 % is found. This range of values represent a significant removal of metals from the water column by the CW which correspond well with the values listed earlier in Table 2.7 (metal removal efficiency observed in field experiments). Total CW system removal of metals in the initial storm water concentration can be calculated as follows:

$$\frac{76720.16 - 14500}{76720.16} = 0.811 \text{ or } 81.1\ \%$$

Although such metal removal rates are not always realized, appropriate design of a CW treatment system could be expected to remove similar or even higher metal percentages. Figure 4.8 shows the CW metal inflow rate as well as the resulting outflow rate of metals from the CW. Figure 4.9 presents the initial metal inflow rate into the detention pond as well as the final CW metal outflow rate.

Figure 4.8
Metal Inflow Rate to CW and CW Metal Outflow Rates

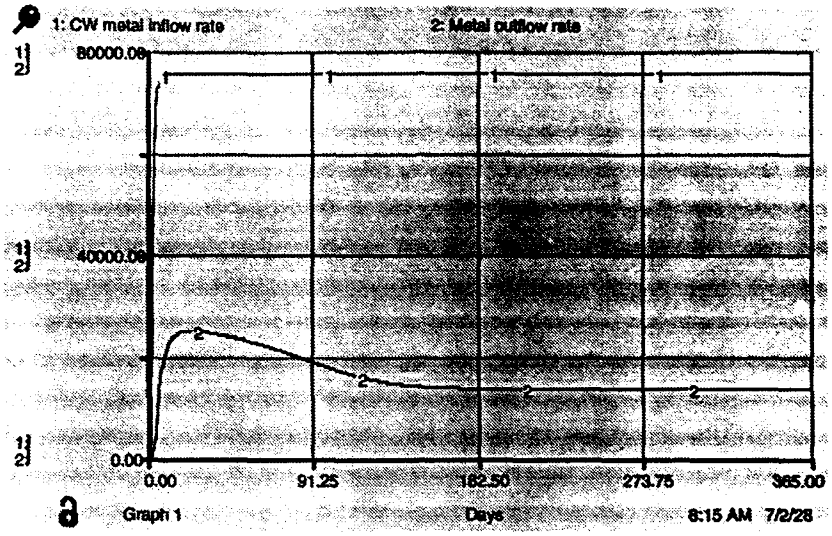
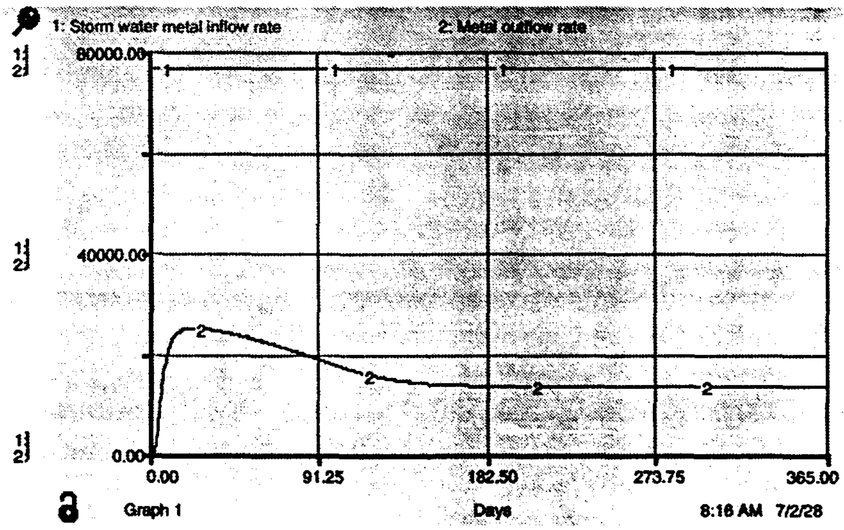


Figure 4.9
Metal Inflow Rate to Detention Pond and CW Metal Outflow Rate



Concentrations of Interest

Metal Concentration in CW Water - The concentration of metal found in the CW water volume is very important to determining whether a CW is an effective storm water best management practice, since this concentration represents the "end of pipe" regulated concentration. Initially this concentration was fairly high due to lack of both plant and

microbial populations, however as both of these communities reached equilibrium levels, the metal concentration in the CW water volume was reduced to about half its start-up value. As could be expected viewing the metal outflow rates presented earlier, the metal concentration in the hypothetical CW went from an initial value of 50 ppb to a high of 20 ppb at CW start-up and tapered off to about 9 ppb. Both one year and ten year graphs are presented at the end of this section in Figures 4.11 and 4.12. The one year graph shows the metal concentration to reach a stable value, however the ten year graph shows a very small continuing rise in metal concentration found in the CW water. This increase represents the ever increasing soil concentration and resuspension of metals into the water column. Although the metal concentration in the soil continues to show substantial increases over time, these increases do not greatly affect the metal concentration in the CW water and thus in its measured outflow. Faulkner found less than one sixth of one percent of metal remained in the water of a CW utilized as a best management practice for mine effluent waste water, while the CW soil accumulated concentrations of metal greater than the concentration in the mine effluent (Hammer/Faulkner, 1990:62). Although Faulkner's research represents a CW receiving high metal concentrations which are not typically characteristic of urban storm water, it does show a relatively small metal concentration in the CW water stock compared to the soil stock accumulation. Thus it could be expected that only a small percentage of metal remains in the CW water column and the predicted hypothetical CW water concentration may be appropriate.

Metal Concentration in CW Soil - The metal concentration found in the soil may be the most important long-term concern of the CW operator due to the sheer magnitude of its accumulation in this location. Unlike the metal concentration in the CW water column which seemed to reach a point within a year where increases in concentration became negligible, the metal concentration in the CW soil continues to see measurable increases. It does not increase linearly, however it takes a much longer time to reach a

point where concentration increases become minimal. Within a year, the metal concentration in the soil became 1.71 ppm at a storm water inflow concentration of 50 ppb. After a ten year period, this concentration became 4.88 ppm. After this point incremental increases became less drastic, however an asymptote was not reached within this time period. This continuing accumulation of metals in the soil does show some potential for long-term regulatory concerns and the possibility of flora and fauna toxicity.

Metal Concentration in Plant Biomass - The curve showing the concentration found in the CW plants follows the soil concentration curve precisely since it is assumed to reach equilibrium conditions immediately as discussed earlier in Chapter III. After one year, the concentration expected in the plant biomass was found to be 0.73 ppm. After a ten year period of operation, the plant concentration became 2.26 ppm. Both of these simulations correspond to storm water input concentrations of 50 ppb. Laboratory experiments with Typha have shown that zinc concentrations in the plant root tissue can reach 1400 mg/kg after dosing with a 10 mg/l solution for a period of one month (Blake, 1987:487). However this value was not observed in either the laboratory or field experiments done by Shutes and others (Morishi/Shutes, 1993:411-412). Comparison of simulation results with Shutes data presented in Chapter II (Table 2.10) shows that hypothetical plant accumulations may be appropriate for some metals, but are probably low for most others depending on initial storm water concentration and frequency of input.

Figure 4.11
Metal Concentrations in CW Water, Soil, and Plant Biomass (1 year)

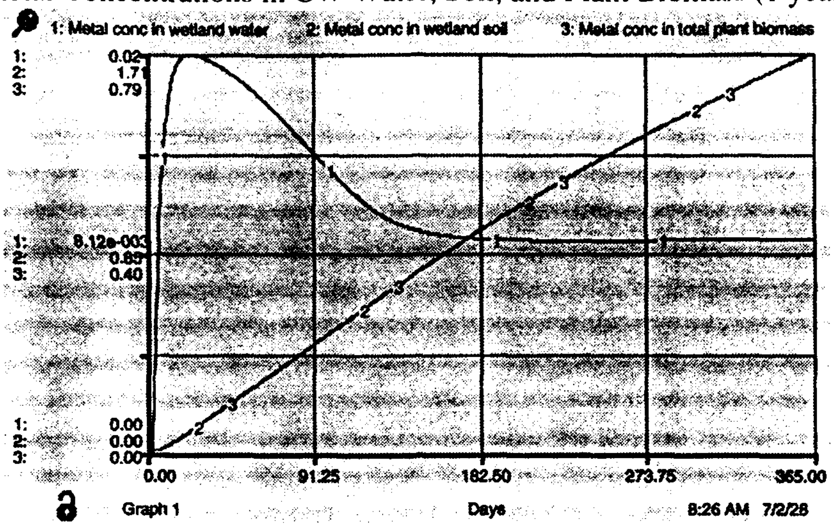
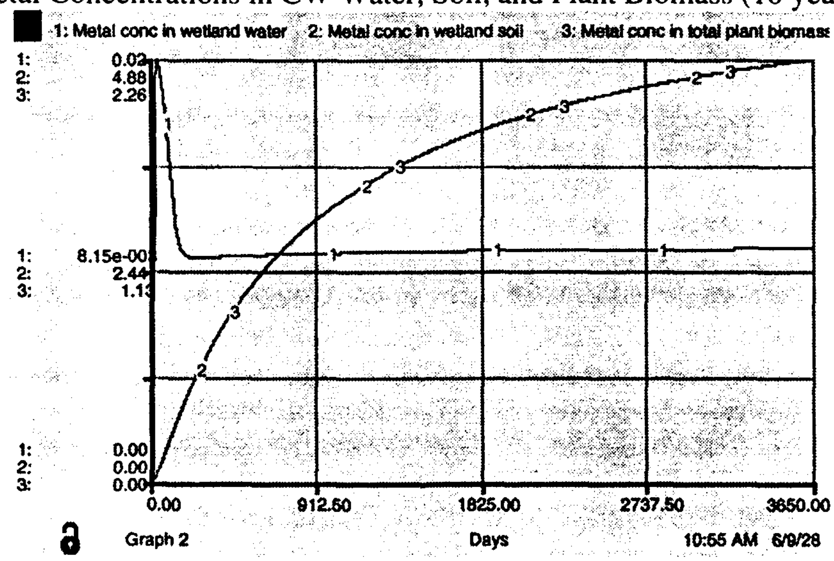


Figure 4.12
Metal Concentrations in CW Water, Soil, and Plant Biomass (10 years)



Parameter Modifications

Although many possible variations of the Stella II model provide ample areas for scrutiny, two carefully selected parameters were chosen. The two parameters consist of

an ordinarily controllable factor (CW size) and one possibly uncontrollable factor (storm water metal concentration). The former factor may be restricted by land availability or monetary funding. Analysis of these two factors should allow assessment of the benefits and costs of various proposed CW designs that depend on the factors of size and metal concentration. The following paragraphs analyze the individual variable factors and briefly explain the model changes that were necessary to simulate the intended variations.

Constructed Wetland Size - This parameter will be site specific, based on land availability and necessary funding requirements, and assumed to be within the control of the CW designer. Since the hypothetical dimensions of the CW (435 meters × 50 meters) require a large amount of land and funding, only smaller CW size variations were considered. CWs of 0.75 standard (the original CW being the standard), 0.5 standard, and 0.25 standard were developed.

To create these smaller versions of the standard CW, many modifications were incorporated. These changes included appropriate reductions in CW area and initial CW water volume in the hydrologic sector. Modification of the CW carrying capacity auxiliary variables in the microbial sector were also required as well as reductions in the initial plant biomass stock of the plant biomass sector. The initial soil volume and the secondary sedimentation rate of the soil sector required reductions as well as the soil concentrations. An appropriate reduction in the microbial population variable affecting the precipitation/absorption rate of the metal stock was also required. All modifications were based on the difference in CW sizes. For example, the 0.5 standard CW was assumed to contain only half the 1.0 standard CW water volume, microbial and plant populations, and CW soil, since it was only half the 1.0 standard CW size. Parameters controlling these stocks were modified to reflect their corresponding reductions in CW size.

Storm Water Metal Concentration - This variable factor is highly site specific and may be uncontrollable after reasonable pollution prevention practices are applied. The effects of ten different storm water metal concentrations ranging from 50 to 500 ppb were simulated for each of the different CW sizes. The maximum measured metal concentration (for a single metal) in the Air Force's group permit application data was 348 ppb. Higher concentrations are not expected to occur on a consistent basis, and the 500 ppb maximum value used in the simulation should not be found at any Air Force installation.

Experimental Factor Results

The following section consists of both graphical and tabular results of the experimental design. Concentrations of interest include metals in the CW water column, soil, and total plant biomass. Results are presented and discussed for each simulated CW size. To portray output that is representative of the simulations, a graph of resultant concentrations of interest at a storm water concentration of 50 ppb is presented for each size of CW. Each graph shows ten years of simulated history, which suffices to inform the reader of the general shape and magnitudes of plotted quantities.

1.0 Standard CW (435 m × 50 m, 21750 m^2)

This CW variation represents the initial model design dimensions with a length to width ratio of almost nine to one. This CW is also the largest of the simulated designs providing a detention time of 13.27 days which is well above the minimum range of 5-7 days. The results, presented earlier in this chapter, show it to be an effective and responsible best management practice at a storm water concentration input of 50 ppb for a duration of ten years. Average metal removal efficiency is approximately 82 %, which shows that this particular CW is an adequate best management practice for the

hypothetical storm water inflow. Metal accumulation in the CW soil attains a value of 5.66 ppm operating for 30 years at a storm water concentration of 50 ppb. This metal accumulation value probably does not represent a toxic concern for the CW designer. The following graph and tabular data represent the results of both higher metal concentrations and varying time durations.

Figure 4.13
Metal Concentrations (50 ppb) in 1.0 Standard
CW Water, Soil, and Plant Biomass (10 years)

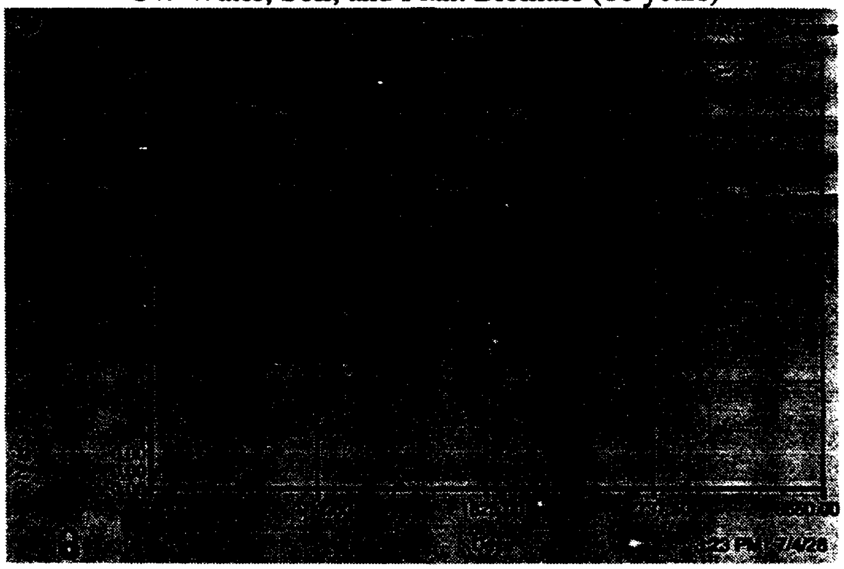


Table 4.1
Metal Concentrations (ppm) in 1.0 Standard
CW Water, Soil, and Plant Biomass (1 year)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0087	.0173	.0260	.0346	.0433	.0519	.0606	.0692	.0779	.0865
Soil Concentration	1.71	3.41	5.12	6.82	8.53	10.23	11.94	13.64	15.35	17.05
Total Plant Concentration	.79	1.58	2.38	3.17	3.96	4.75	5.54	6.33	7.13	7.92

Table 4.2
Metal Concentrations (ppm) in 1.0 Standard
CW Water, Soil, and Plant Biomass (5 years)

Input Conc.	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Water Concentration	.0089	.0178	.0267	.0355	.0444	.0533	.0622	.0711	.0800	.0889
Soil Concentration	4.06	8.11	12.17	16.22	20.28	24.34	28.39	32.45	36.50	40.56
Total Plant Concentration	1.88	3.77	5.65	7.53	9.41	11.30	13.18	15.06	16.95	18.83

Table 4.3
Metal Concentrations (ppm) in 1.0 Standard
CW Water, Soil, and Plant Biomass (15 years)

Input Conc.	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Water Concentration	.0090	.0180	.0270	.0360	.0450	.0540	.0630	.0720	.0810	.0900
Soil Concentration	5.24	10.47	15.71	20.94	26.18	31.41	36.65	41.88	47.12	52.35
Total Plant Concentration	2.43	4.86	7.29	9.72	12.15	14.58	17.01	19.44	21.88	24.31

Table 4.4
Metal Concentrations (ppm) in 1.0 Standard
CW Water, Soil, and Plant Biomass (30 years)

Input Conc.	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Water Concentration	.0090	.0181	.0271	.0362	.0452	.0542	.0633	.0723	.0814	.0904
Soil Concentration	5.66	11.32	16.98	22.64	28.30	33.96	39.62	45.28	50.94	56.64
Total Plant Concentration	2.63	5.26	7.89	10.52	13.15	15.78	18.41	21.04	23.67	26.29

<u>0.75 Standard CW (326.25 m × 50 m, 16312.5 m^2)</u>

This CW variation represents modified model design dimensions with a length to width ratio of about six and a half to one. Though this CW functions nearly as well as the 1.0 standard size CW, its reduced size does increase metal concentrations in all three locations of interest. After 30 years of operation, the average metal removal efficiency is approximately 75 %. This efficiency shows it could reasonably be considered as an

effective best management practice for this particular storm water inflow. Metal accumulation in the CW attains higher values than the standard CW discussed above, but toxic conditions will probably not be encountered. At a storm water concentration of 50 ppb, the soil is expected to accumulate about 7 ppm, probably not a realistic threat to CW communities. Figure 4.14 represents a general accumulation curve found at 50 ppb for a period of ten years. The tabular data represent the results of all simulated combinations of concentration and time durations at this CW size.

Figure 4.14
Metal Concentrations (50 ppb) in 0.75 Standard
CW Water, Soil, and Plant Biomass (10 years)

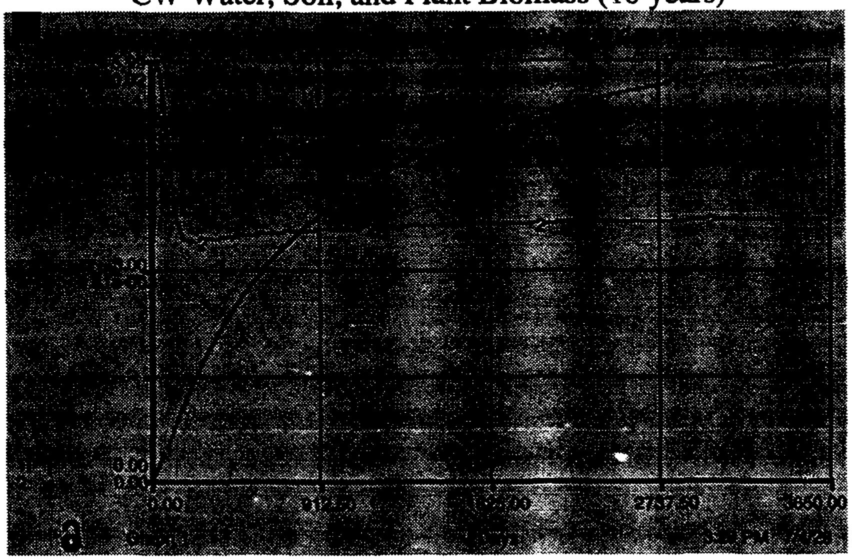


Table 4.5
Metal Concentrations (ppm) in 0.75 Standard
CW Water, Soil, and Plant Biomass (1 year)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0112	.0224	.0336	.0449	.0561	.0673	.0785	.0897	.1009	.1120
Soil Concentration	2.13	4.25	6.38	8.51	10.63	12.76	14.88	17.01	19.14	21.26
Total Plant Concentration	0.99	1.97	2.96	3.95	4.94	5.92	6.91	7.90	8.88	9.87

Table 4.6
Metal Concentrations (ppm) in 0.75 Standard
CW Water, Soil, and Plant Biomass (5 years)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0119	.0238	.0357	.0476	.0595	.0714	.0833	.0952	.1071	.1190
Soil Concentration	5.01	10.03	15.04	20.06	25.07	30.09	35.10	40.12	45.13	50.15
Total Plant Concentration	2.33	4.66	6.98	9.31	11.64	13.97	16.29	18.62	20.95	23.28

Table 4.7
Metal Concentrations (ppm) in 0.75 Standard
CW Water, Soil, and Plant Biomass (15 years)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0122	.0244	.0366	.0488	.0610	.0732	.0854	.0976	.1098	.1220
Soil Concentration	6.41	12.83	19.24	25.66	32.07	38.49	44.90	51.32	57.73	64.15
Total Plant Concentration	2.98	5.96	8.94	11.91	14.89	17.87	20.84	23.82	26.80	29.78

Table 4.8
Metal Concentrations (ppm) in 0.75 Standard
CW Water, Soil, and Plant Biomass (30 years)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0123	.0246	.0369	.0492	.0615	.0738	.0861	.0984	.1107	.1230
Soil Concentration	6.91	13.82	20.73	27.64	34.55	41.46	48.37	55.28	62.19	69.10
Total Plant Concentration	3.21	6.42	9.63	12.83	16.04	19.25	22.45	25.66	28.87	32.08

<u>0.5 Standard CW (217.5 m × 50 m, 10875 m^2)</u>

This CW variation represents modified model design dimensions with a length to width ratio slightly greater than four to one. This CW functions less efficiently than the two larger CWs discussed previously. Its metal removal efficiency after 30 years drops to 61 %. Much of the marginal behavior and reduced removal capacity stems from its reduced volume which provides a detention time of only 5.18 days. This value may still

be acceptable, however it begins to border on the minimum range of effective detention times. Sedimentation of the smaller particles reaching the CW is not optimized since the time constant associated with their settling rate is not always being met. This CW size seems to represent the minimum size necessary to effectively remove metals from the incoming storm water flow. At 50 ppb storm water concentration, a metal accumulation of approximately 9 ppm in the soil is expected after 30 years of operation. This accumulation of metal is probably not toxic to most if not all wetland plants and animals, depending of course on the metal species in question. The following graph represents a general accumulation curve found at 50 ppb for a period of ten years while the tabular data represent the results of all possible combinations of concentration and time permutations.

Figure 4.15
Metal Concentrations (50 ppb) in 0.5 Standard
CW Water, Soil, and Plant Biomass (10 years)

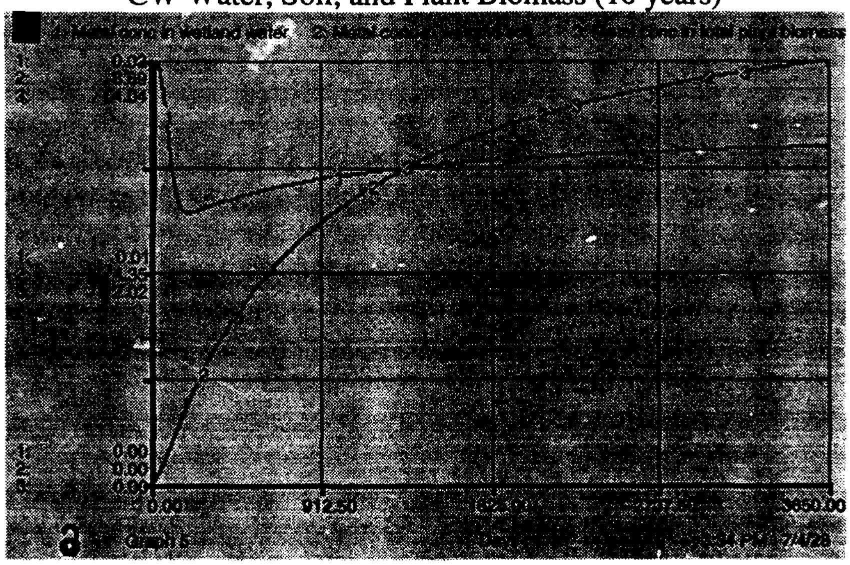


Table 4.9
Metal Concentrations (ppm) in 0.5 Standard
CW Water, Soil, and Plant Biomass (1 year)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0162	.0325	.0487	.0649	.0812	.0974	.1136	.1298	.1459	.1621
Soil Concentration	2.95	5.91	8.86	11.81	14.76	17.72	20.68	23.63	26.59	29.54
Total Plant Concentration	1.37	2.74	4.11	5.48	6.85	8.22	9.59	10.96	12.33	13.71

Table 4.10
Metal Concentrations (ppm) in 0.5 Standard
CW Water, Soil, and Plant Biomass (5 years)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0187	.0374	.0561	.0747	.0935	.1120	.1309	.1496	.1683	.1870
Soil Concentration	7.23	14.46	21.69	28.92	36.15	43.40	50.61	57.84	65.07	72.30
Total Plant Concentration	3.36	6.72	10.08	13.44	16.80	20.15	23.52	26.88	30.24	33.60

Table 4.11
Metal Concentrations (ppm) in 0.5 Standard
CW Water, Soil, and Plant Biomass (15 years)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0199	.0398	.0597	.0796	.0995	.1194	.1393	.1592	.1791	.1990
Soil Concentration	9.31	18.62	27.93	37.24	46.55	55.86	65.17	74.48	83.79	93.06
Total Plant Concentration	4.32	8.64	12.96	17.28	21.60	25.92	30.24	34.56	38.88	43.20

Table 4.12
Metal Concentrations (ppm) in 0.5 Standard
CW Water, Soil, and Plant Biomass (30 years)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0203	.0406	.0609	.0812	.1015	.1218	.1421	.1624	.1827	.2030
Soil Concentration	10.00	20.01	30.01	40.01	50.01	60.02	70.02	80.02	90.02	100.03
Total Plant Concentration	4.64	9.28	13.92	18.56	23.20	27.84	32.48	37.12	41.76	46.44

0.25 Standard CW (108.75 m × 50 m, 5437.5 m²)

This CW variation represents modified model design dimensions with a length to width ratio slightly greater than two to one. This CW does not function as a BMP for this hypothetical storm water flow. Its reduced volume creates a detention time of 3.3 days which is insufficient time for the CW processes to adequately remove metal from the storm inflow. Its metal removal efficiency is approximately 34 %, hardly a best management practice worth considering since most of the metal in the storm water inflow is discharged downstream creating a potential compliance issue. Even though the majority of metal flows through this CW without effect, metal accumulation in the soil and plants is the highest of the four CW sizes evaluated. Potential toxicity and regulatory concern over metal accumulation in this CW is much less clear and some concern may be warranted. Figure 4.16 represents a general accumulation curve found at 50 ppb for a period of ten years while the tabular data represent the results of all possible combinations of concentration and time durations for this CW size.

Figure 4.16
Metal Concentrations (50 ppb) in 0.25 Standard
CW Water, Soil, and Plant Biomass (10 years)

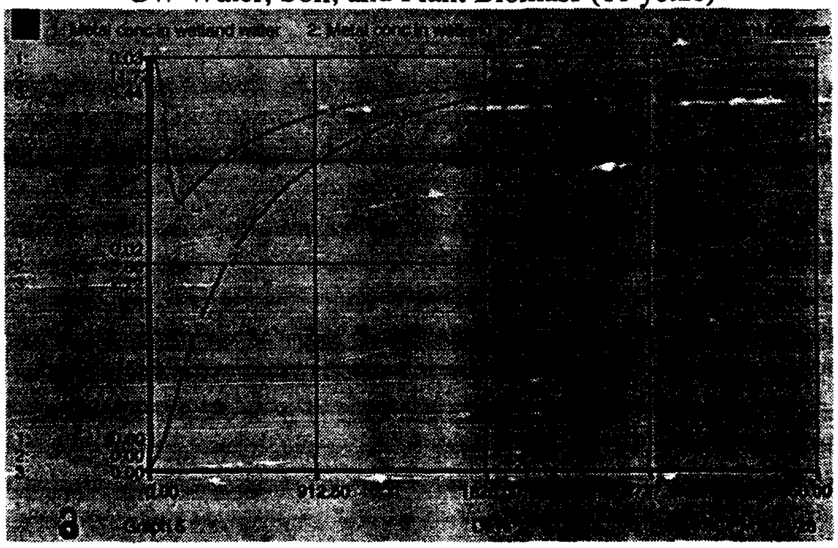


Table 4.13
Metal Concentrations (ppm) in 0.25 Standard
CW Water, Soil, and Plant Biomass (1 year)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0244	.0488	.0732	.0976	.1220	.1464	.1708	.1952	.2196	.2440
Soil Concentration	5.29	10.58	15.87	21.16	26.45	31.74	37.03	42.32	47.61	52.92
Total Plant Concentration	2.46	4.92	7.38	9.84	12.30	14.76	17.22	19.68	22.14	24.57

Table 4.14
Metal Concentrations (ppm) in 0.25 Standard
CW Water, Soil, and Plant Biomass (5 years)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0308	.0616	.0924	.1232	.1540	.1848	.2156	.2464	.2772	.3081
Soil Concentration	10.60	21.20	31.80	42.40	53.00	63.60	74.20	84.80	95.40	106.01
Total Plant Concentration	4.92	9.84	14.76	19.68	24.60	29.52	34.44	39.36	44.28	49.21

Table 4.15
Metal Concentrations (ppm) in 0.25 Standard
CW Water, Soil, and Plant Biomass (15 years)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0326	.0652	.0978	.1304	.1630	.1956	.2282	.2608	.2934	.3260
Soil Concentration	12.09	24.18	36.27	48.36	60.45	72.54	84.63	96.72	108.81	120.89
Total Plant Concentration	5.61	11.22	16.83	22.44	28.05	33.66	39.27	44.88	50.49	56.09

Table 4.16
Metal Concentrations (ppm) in 0.25 Standard
CW Water, Soil, and Plant Biomass (30 years)

Input Conc.	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
Water Concentration	.0330	.0660	.0991	.1321	.1651	.1981	.2311	.2641	.2971	.3301
Soil Concentration	12.42	7.96	11.94	15.92	19.90	23.88	27.86	31.84	35.82	124.17
Total Plant Concentration	5.76	11.52	17.28	23.04	28.81	34.56	40.32	46.08	51.84	57.61

Conclusions

Based on the data presented in this section, it seems apparent that properly sized CW systems can offer an effective technology approach to controlling metal concentrations in AF storm water. Although the CW sediment does seem to attain a fairly high concentration of metals, with respect to the input concentration, the accumulation concentrations tend to level off as time goes on. This decreasing rate of metal accumulation is due primarily to the continued addition of sediment which dilutes the rate of metal accumulation in CW soil and biomass. Thus if the CW designer and regulatory agencies can tolerate with the short term (5 year) metal accumulation concentrations, long term (30 or more years) concentrations should not be greatly increased.

The plant concentrations in all but the 0.25 CW probably do not represent toxic levels to the selected plant species in the CW. Some plants can tolerate very high metal concentrations with little or no observable effects in growth and net primary production rates. Shutes and others found no observable toxic effects to both Typha and Juncus plants in laboratory and field experiments where plants had accumulated a minimum of 5 ppm of various metals (Morishi/Shutes, 1993:411). However, other species of plants may succumb to much lower metal concentrations if other stressors are also present. The potential for plant toxicity is highly variable depending on plant species, type of metal, and CW conditions. Since plant tolerance to metals may be highly site specific, the CW designer should carefully select the appropriate species depending on expected pollutant and its respective concentration.

V. Conclusions and Recommendations

The purpose of this research was to analyze and model the potential efficiency and danger of trace metal accumulation in a constructed wetland (CW) implemented as a best management practice to assist Base Civil Engineers and Environmental Managers in complying with National Pollutant Discharge Elimination System (NPDES) storm water discharge requirements at USAF installations. This chapter presents the overall conclusions to the investigative questions presented in Chapter I, as well as some recommendations for future research.

Conclusions

Investigative Question One: Which trace metals and respective concentrations can be expected to be found in storm water produced at a typical AF installation?

A wide variety of trace metals and concentrations of such metals can be found in storm water produced at AF installations. Based on the data sent to the EPA as partial fulfillment of the Air Force storm water group application which was taken from eleven different AF installations, seven different metals were identified. These metals included Antimony, Arsenic, Cadmium, Copper, Lead, Selenium, and Zinc. Concentrations found during the two required storm water sampling rounds ranged from a high of 348 μg/L (Zinc at Keesler AFB) to undetected concentrations. Some concern has arisen over the non-conformity of metal sampling detection levels. Since the EPA has not yet specified regulatory levels for metals in airfield storm water, rather focusing on biochemical oxygen demand from de-icing chemicals, various detection levels were incorporated during this most recent data gathering event. Limits of detection as high as 100 and 50 μg/L were common throughout the sampling efforts, while some bases incorporated much more stringent detection limits. Such inconsistency in determining detection limits and

regulatory requirements for trace metals can most surely be expected to be modified in future EPA required sampling efforts.

The metals typically found in storm water runoff as defined by Metcalf and Eddy were all found to be present in AF storm water in expected concentrations. Nickel, which may also be considered to be commonly found in storm water, was not present in any AF storm water samples, however this absence may be due to the detection limit inconsistencies and lack of sampling requirements. Other metals including Antimony, Arsenic, Cadmium, and Selenium were each detected more than once, however all but the last metal were detected at concentration levels of less than 40 μg/L. Overall pollutant concentrations determined by these two sampling rounds found AF storm water to be very typical of average storm water. Standardization of AF sampling detection levels, pollutants of concern, and corresponding tabulation of storm water data should be undertaken in the future.

Investigative Question Two: What processes does a CW perform to reduce metal concentrations in storm water and where do metals accumulate to create potentially toxic conditions in the CW?

Many different removal processes are involved with trace metal removal from storm water entering a CW. These processes are found almost universally in both constructed and naturally occurring wetlands. Many of these removal processes are similar to those found in municipal sewage treatment systems however they do not typically require extensive maintenance and operation costs to produce long term efficiency. Processes that directly affect metal concentrations contained in the incoming storm water volume include sedimentation, flocculation, precipitation, adsorption, and plant uptake. However other wetland removal processes, such as nutrient removal,

indirectly affect metal removal by influencing microbial and plant communities within the CW.

The majority of these processes are directly dependent on the particle size distribution of the metal concentration. Metals can be found in the water column in both particulate and dissolved phases. Larger metal contaminated particulate matter is affected by those CW processes such as sedimentation, while smaller particulate matter is removed more readily by adsorption and flocculation. The metals dissolved in the storm water volume entering the CW are most readily affected by precipitation. Those metal particles and dissolved phase precipitates which enter the CW soil mass can be affected by plant uptake, however this process typically does not remove metals from the water column or the CW itself. Plants tend to take up metals primarily through the CW soil and typically do not degrade such pollutants. This eventually dictates that unless the entire plant is removed, the metals will return to the CW soil when the plant dies.

Investigative Question Three: Can these processes be effectively represented in a model to predict metal accumulation locations and concentrations of varying storm water inputs and CW sizes?

Although the complexity of modeling a wetland in its entirety is a truly formidable if not impossible task, it is however, possible to model parts of the wetland to effectively represent reality for the purposes of predicting resulting metal concentrations. Many of the individual removal processes performed in a CW are currently known and can in most cases be quantified. The fact that individual processes have been described and can be applied does not guarantee that a model will make a completely accurate representation of trace metal removal in a CW. No current model exists that can reasonably make such a claim. Application of known CW processes is a one-dimensional cut at creating a model. Many synergies and complementary actions are involved in each

process relation which can vary greatly depending on site conditions. It is important to understand that not every facet of a wetland needs to be meticulously detailed in order for a model to make a reasonable assessment of reality. Such is the essence of modeling. Every model makes assumptions of certain parameters in order to provide results within a reasonable time frame and scope of interest. The model created for this research effort is no different. Many assumptions were made throughout the modeling process, however it is thought that such simplifications or omissions do not detract from the overall performance of the model (i.e., it is possible for herbivores near the hypothetical CW to consume plants and thus remove metals, however the magnitude of such metal removal is inconsequential and thus omitted). Therefore, the parameters and processes left out or simplified in the model are as important to the overall model integrity as those processes simulated in the model. Although these limitations can be complex, they can also be managed. As the famous author once said that one can never prove anything, merely one can only disprove something. This model is merely one such hypothesis of a multitude of CW scenarios. Its purpose was to provide a general outline for trace metal removal within a CW for a specific and ideal situation. It is left to the reader to determine the adequacy of the assumptions and the final determination of whether the model can accommodate the reality of their own scenario.

Investigative Question Four: What information is currently available on design and maintenance procedures to help AF base level managers create and operate a CW as a storm water BMP to effectively mitigate trace metals while minimizing the toxicity of trace metal accumulation?

Both design and maintenance factors are highly important to CW metal removal efficiency and longevity when applied as a storm water BMP. Design factors to safely optimize trace metal removal include creating conditions in the CW where adequate sites

for dissolved and particulate metals are able to bind with soil and plant material. Obvious considerations include design of a large enough CW to adequately reduce the storm water velocity for a detention period greater than five days as well as planning for sediment removal prior to the CW (detention ponds). Less obvious design considerations include utilizing gravel substrate to support high hydraulic loadings and implement subsurface sheet flow and planning for sediment removal within the CW itself. Maintenance procedures include regular removal of sediment from the detention pond as well as regular monitoring procedures of metal concentrations in the CW soil and plant tissues. These concerns are vital to creating and maintaining a CW's metal removal capacity and avoiding long term potential toxicity and regulatory issues.

Recommendations for Future Research

This research was prompted by the anticipation of more stringent NPDES storm water requirements and the advertisement of implementing CWs as possible BMPs. The Air Force must be able to accurately predict the potential accumulation, toxicity, and longevity of CWs receiving storm water. In order to aide in this development, the following topics may require future research.

1. Using the model created here validate and/or modify it to more accurately represent reality with data from a CW receiving AF storm water.

2. Using the model created here, quantify and apply removal values and accumulation rates associated with a particular metal species to determine accumulation and potential toxicity.

3. Create another model using the STELLA II software which represents BOD degradation and removal in a CW receiving de-icing contaminated flows as this concern seems to be at the forefront of EPA concerns about airfields.

4. Perform a risk assessment on a CW receiving AF storm water to determine potential for AF liability if such a BMP is implemented.

Appendix A. Rational Equation "C" Values For Various Surfaces

Description of Area	**C**
Business	
Downtown	0.70-0.95
Neighborhood	0.50-0.70
Residential	
Single-family	0.30-0.50
Multiunits, detached	0.40-0.60
Multiunits, attached	0.60-0.75
Residential suburban	0.25-0.40
Apartment	0.50-0.70
Industrial	
Light	0.50-0.80
Heavy	0.60-0.90
Parks, cemeteries	0.10-0.25
Playgrounds	0.20-0.35
Railroad yard	0.20-0.35
Unimproved	0.10-0.30
Character of Surface	
Pavement	0.70-0.95
Asphalt and concrete	0.70-0.85
Brick	0.75-0.95
Roofs	
Lawns, sandy soil	
Flat, up to 2 % grade	0.05-0.10
Average, 2-7 % grade	0.10-0.15
Steep, over 7 %	0.15-0.20
Lawns, heavy soil	
Flat, up to 2 % grade	0.13-0.17
Average, 2-7 % grade	0.18-0.22
Steep, over 7 %	0.25-0.35

Fetter, Applied Hydrology, page 50.

Appendix B. Preliminary Constructed Wetland Model

Equations

Concentrations of Interest

Metal_conc_in_detention_sediment = Metals_in_detention_sediment/Soil_in_DP_sediment
DOCUMENT: This concentration represents the amount per volume of soil that metals accumulate in the detention pond sediment prior to removal. The units are mg(of metals)/kg(of soil sediment) or ppm.

Metal_conc_in_detention_water = Metals_in_detention_water/(DP_volume*1000)
DOCUMENT: This concentration represents the amount of metals(mg) per volume of detention pond water in liters. Since the detention pond volume is initially in meters cubed, the conversion is necessary to produce a concentration in ppm.

Metal_conc_in_total_plant_biomass = Metal_conc_in_harv_plant_biomass*1.857
DOCUMENT: This concentration represents the concentration of metal accumulation in the total plant in mg(of metals)/kg(of plant biomass). The Morishi text has an article by Shutes and others (62S) that accounts for both metal dosing experiments and field observations of metal uptake by cattail and reed plants. It was observed that on average almost twice as much of the metal concentration present in the wetland was taken up by the unharvestable root and rhizome parts of the plant. Therefore this calculation of total metal concentration in the plant biomass is necessary to account for possible plant toxicity.

Metal_conc_in_wetland_soil = Metals_in_wetland_soil/(Soil_in_CW-47038725)
DOCUMENT: This concentration accounts for the amount of metals accumulating in the top 30 cm of wetland soil initially, and with the top 30 cm plus what soil is deposited as the simulation progresses. The 47038725 kg value represents 1.5 meters of uncontaminated soil below active soil interactions in the top 30 cm such as plant uptake, sedimentation, resuspension, and erosion. A soil weight of 90 lb/ft or 1441.8 kg/meter cubed was assumed.

Metal_conc_in_wetland_water = Metals_in_wetland_water/(CW_volume*1000)
DOCUMENT: This concentration represents the amount, per volume of water, of metals that are present in the wetland water at any given time. Units of concentration are given in mg(of metals)/l(of water). Since the wetland volume is not in liters, the conversion factor is added to the equation to give mg/l or ppm.

Soil_conc_in_CW_water = Soil_in_CW_water/((Actual_water_level)*21750)
DOCUMENT: This equation converts the soil in wetland water (kg) to a kg/meter cubed concentration for use in the sedimentation part of the soil compartment. To obtain this value, it was assumed that the water of concern here was only the 20 cm above the wetland soil, since the rest of the wetland water is in the saturated soil below. The actual water level was used to calculate the volume above the wetland soil at any given time which produces a meters cubed value for this volume.

Soil_conc_in_DP_water = Soil_in_DP_water/(DP_volume*1000)
DOCUMENT: This concentration represents the soil concentration in the detention pond water. Units are given in kg/l.
Soil_conc_in_wetland_outflow = Soil_loss_rate/CW_outflow

DOCUMENT: This concentration represents the soil present in the wetland outflow water. Units are given in kilograms per meter cubed.

Hydrology

CW_volume(t) = CW_volume(t - dt) + (CW_inflow - CW_outflow - CW_evapotranspiration) * dt
INIT CW_volume = 20000
DOCUMENT: This volume represents the wetland volume. Its design capacity is 20,000 meters cubed. Dimensions are 435 meters long by 50 meters wide by 2 meters deep. 1.8 meters of the depth are taken up by saturated soil with a porosity of 0.4.

CW_inflow = DP_volume*.65
DOCUMENT: This outflow represents the rate at which water in the detention pond volume will leave and enter the wetland. The detention pond is designed to evacuate > 95% of its contents to the wetland in three days or less.

CW_outflow = GRAPH(Effective_water_level-2.475)
(0.00, 0.00), (0.0833, 12.1), (0.167, 69.2), (0.25, 191), (0.333, 391), (0.417, 687), (0.5, 1081), (0.583, 1587), (0.667, 2222), (0.75, 2980), (0.833, 3874), (0.917, 4925), (1.00, 6117)
DOCUMENT: This flow is merely the hydraulic flow rate out of the wetland given in meters cubed per day.

CW_evapotranspiration = CW_volume*.0005250548
DOCUMENT: This outflow represents for the evapotranspiration rate seen by the wetland volume. Evapotranspiration rate is based on 19% calculated for Warner-Robins AFB, GA.

DP_volume(t) = DP_volume(t - dt) + (Storm_water_rate - CW_inflow - DP_evapotranspiration) * dt
INIT DP_volume = 1
DOCUMENT: This volume represents the detention pond volume of water. The detention pond design capacity is 5000 meters cubed with dimensions of 50 meters by 50 meters by 2 meters deep. Units are in meters cubed.

Storm_water_rate = Average_rainfall_intensity*Runoff_coefficient*Watershed_area*.0028*86400
DOCUMENT: This rate produces constant storm inflows in meters cubed per day.

CW_inflow = DP_volume*.65
DOCUMENT: This outflow represents the rate at which water in the detention pond volume will leave and enter the wetland. The detention pond is designed to evacuate > 95% of its contents to the wetland in three days or less.

DP_evapotranspiration = DP_volume*.000520548
DOCUMENT: This outflow represents the evapotranspiration rate seen by the detention pond volume. Evapotranspiration rate is based on 19% found in the water budget data for Warner-Robins AFB, GA. Outflow is in meters cubed per day.
Actual_water_level = (Effective_water_level-2.475)/3.2808

DOCUMENT: This level represents the level of the water above the wetland soil. This level is important to living communities in the wetland. Units are in meters.

Average_rainfall_intensity = .140946804
DOCUMENT: This value is the average rainfall experienced by Atlanta GA in mm/hour.

CW_detention_time = CW_volume/CW_outflow
DOCUMENT: This value represents the time it will take for water entering the wetland to find its way out. Units are given in days.

DP_detention_time = DP_volume/CW_inflow
DOCUMENT: This equation produces the detention time that is expected for water entering the detention pond. Units are given as days. State of Maryland design information, Shields article, and Akan article.

Effective_water_level = ((CW_volume/21750)*3.2808)
DOCUMENT: This equation first subtracts the stored volume of water (in soil) from the total wetland water volume. Then divides by the area in meters squared to get meters of depth above soil level. Then the depth change rate factor adds for soil accumulation's affect on the wetland water level. The final value is the depth of water above the soil in the wetland in feet.

Runoff_coefficient = .9
DOCUMENT: This factor represents the landscape surface of the watershed area. Paved areas typically have a high value (all or almost all runoff is entering the storm water rate versus filtering into the ground) while vegetated areas are usually lower.

Watershed_area = 50
DOCUMENT: This value represents the watershed area of concern in hectares, which equate to 10,000 meters squared for each hectare. So 50 hectares would equal 50,000 square meters.

Metal

Metals_in_detention_sediment(t) = Metals_in_detention_sediment(t - dt) + (Metal_sedimentation_rate - Metal_sediment_removal) * dt
INIT Metals_in_detention_sediment = 1
DOCUMENT: This stock represents the metals in mg present in the detention pond's sediment at any given time.

Metal_sedimentation_rate = Metal_conc_in_suspended_soil*Primary_sedimentation
DOCUMENT: This flow rate represents the flow of metals from the detention pond water volume to the detention pond sediment. It is assumed that this flow is directly dependent on the sedimentation rate of particulate matter from the soil compartment. This assumption does not take into account the fraction of metals that is in solution that would precipitate out of solution without the help of particulate sedimentation. This would seem reasonable since, detention time in the detention pond is only 1.54 days, typically insufficient time for precipitation to have a major impact. Units of flow are given in mg/day.

Metal_sediment_removal = Metal_conc_in_detention_sediment*Sediment_removal
DOCUMENT: This outflow of metals represents the outflow of metals present in the detention pond sediment and their respective concentration in the removal fraction of soil sediment that is removed from the detention pond in the soil compartment. Units are in mg/day.

Metals_in_detention_water(t) = Metals_in_detention_water(t - dt) + (Storm_water_metal_inflow_rate - CW_metal_inflow_rate - Metal_sedimentation_rate) * dt
INIT Metals_in_detention_water = 0
DOCUMENT: This stock represents the accumulation of metals in mg in the detention pond water volume.

Storm_water_metal_inflow_rate = Storm_water_rate*Storm_water_metal_concentration
DOCUMENT: This equation will return metal inflow values in mg/day.

CW_metal_inflow_rate =
(Metal_conc_in_suspended_soil*Soil_conc_in_DP_water+(Metal_conc_in_detention_water*1000))*CW_inflow
DOCUMENT: This flow represents that fraction of metals associated with the unsettleable soil fraction and the settleable sediment that is not removed by the detention pond due to less than perfect efficiency which continues on to the wetland water volume. Units are in mg/day.

Metal_sedimentation_rate = Metal_conc_in_suspended_soil*Primary_sedimentation
DOCUMENT: This flow rate represents the flow of metals from the detention pond water volume to the detention pond sediment. It is assumed that this flow is directly dependent on the sedimentation rate of particulate matter from the soil compartment. This assumption does not take into account the fraction of metals that is in solution that would precipitate out of solution without the help of particulate sedimentation. This would seem reasonable since, detention time in the detention pond is only 1.54 days, typically insufficient time for precipitation to have a major impact. Units of flow are given in mg/day.

Metals_in_wetland_soil(t) = Metals_in_wetland_soil(t - dt) + (Secondary_metal_sedimentation_rate + Metal_return_rate + Precipitation\Adsorption_rate - M_resuspension_rate - Metal_removal_rate) * dt
INIT Metals_in_wetland_soil = 0
DOCUMENT: This stock represents the accumulation of metals in the wetland soil. Units of metal accumulation are in mg.

Secondary_metal_sedimentation_rate = Metal_conc_in_suspended_soil*Secondary_sedimentation
DOCUMENT: This flow rate represents the flow of metals in the wetland water to the wetland soil through secondary sedimentation or the sedimentation provided by the wetland removal processes. This sedimentation of metals is tied directly to sedimentation of particulate matter in the wetland and does not account for precipitation of metals that could be a factor in a constructed wetland depending on pH and temperature. Units of flow are in mg/day.

Metal_return_rate = Metal_conc_in_harv_plant_biomass*Plant_decomposition_rate
DOCUMENT: This flow rate represents the return of metals from the plant biomass stock back to the wetland soil stock. Units are in mg/day.

Precipitation\Adsorption_rate =
Metals_in_wetland_water*P_ph_conversion*WT_conversion*(Microbial_population/2.41E16)*.75
M_resuspension_rate = Metal_conc_in_wetland_soil*Soil_resuspension_rate
DOCUMENT: This flow rate represents the resuspension of metal particulates along with the resuspension of soil particles from the wetland soil back into the wetland water. Units are in mg/day.

Metal_removal_rate = Harvest_outflow*Metal_conc_in_harv_plant_biomass
DOCUMENT: This outflow represents the harvesting of plant biomass and its respective metal concentration for proper disposal outside the wetland. Units are in mg/day.

Metals_in_wetland_water(t) = Metals_in_wetland_water(t - dt) + (CW_metal_inflow_rate + M_resuspension_rate - Secondary_metal_sedimentation_rate - Precipitation\Adsorption_rate - Metal_outflow_rate) * dt
INIT Metals_in_wetland_water = 0
DOCUMENT: This stock represents the accumulation of metals in the wetland water. Units are in mg of metals.

CW_metal_inflow_rate =
(Metal_conc_in_suspended_soil*Soil_conc_in_DP_water+(Metal_conc_in_detention_water*1000))*CW_inflow
DOCUMENT: This flow represents that fraction of metals associated with the unsettleable soil fraction and the settleable sediment that is not removed by the detention pond due to less than perfect efficiency which continues on to the wetland water volume. Units are in mg/day.

M_resuspension_rate = Metal_conc_in_wetland_soil*Soil_resuspension_rate
DOCUMENT: This flow rate represents the resuspension of metal particulates along with the resuspension of soil particles from the wetland soil back into the wetland water. Units are in mg/day.

Secondary_metal_sedimentation_rate = Metal_conc_in_suspended_soil*Secondary_sedimentation
DOCUMENT: This flow rate represents the flow of metals in the wetland water to the wetland soil through secondary sedimentation or the sedimentation provided by the wetland removal processes. This sedimentation of metals is tied directly to sedimentation of particulate matter in the wetland and does not account for precipitation of metals that could be a factor in a constructed wetland depending on pH and temperature. Units of flow are in mg/day.

Precipitation\Adsorption_rate =
Metals_in_wetland_water*P_ph_conversion*WT_conversion*(Microbial_population/2.41E16)*.75
Metal_outflow_rate = Metal_conc_in_wetland_water*CW_outflow*1000
Metal_conc_in_harv_plant_biomass = Metal_conc_in_wetland_soil*.25
DOCUMENT: This concentration represents the amount of metals present in the harvestable plant biomass, or the metals present in the plant leaf or stem parts. Uptake is considered to be at an equilibrium condition at all times where plant concentration of metals quickly comes to an equilibrium value based on the concentration in the soil. The rate at which this equilibrium value is reached is immediate in this simulation although weeks or even months could pass in reality before equilibrium is reached. The time between metal concentration in the soil affecting the equilibrium concentration is assumed to be small in comparison to the total period of concern and thus this delay makes little difference in overall simulation accuracy. This value is given in mg(of metals)/kg(of plant biomass) or ppm.

Metal_conc_in_suspended_soil = ((Storm_water_metal_concentration/1000)*.5)/1.4418
DOCUMENT: This equation represents the concentration of metals bound to the suspended soil particles in the detention pond. Since the storm water metal concentration has units of ug/l, it is divided by 1000 to produce mg/l or ppm. The storm water metal concentration is assumed to be divided evenly between particulate and solute, thus the .5 multiplier. Lastly, liters of soil need to be converted to kilograms which is done by dividing by the 1.4418 factor which accounts for the average soil weight of 1441.8 kg/meters cubed. Units are given in mg/kg.

Storm_water_metal_concentration = 50
DOCUMENT: This value represents the expected total value (both particulate and dissolved) of metal concentration in the incoming storm water that will enter the wetland. Units are in ug/l.

P_ph_conversion = GRAPH(pH)
(0.00, 1.00), (1.00, 1.00), (2.00, 1.00), (3.00, 1.00), (4.00, 1.00), (5.00, 1.00), (6.00, 0.95), (7.00, 0.87), (8.00, 0.79), (9.00, 0.59), (10.0, 0.27), (11.0, -0.07), (12.0, -0.39), (13.0, -0.7), (14.0, -1.00)
DOCUMENT: This graph represents the effect of pH on the precipitation rate of heavy metals.

Microbial Population

WT_conversion = GRAPH(Water_temperature)
(0.00, 0.00), (10.0, 0.1), (20.0, 0.2), (30.0, 0.3), (40.0, 0.4), (50.0, 0.5), (60.0, 0.6), (70.0, 0.7), (80.0. 0.8), (90.0, 0.9), (100, 1.00)
Microbial_population(t) = Microbial_population(t - dt) + (Birth_inflow - Death_outflow) * dt
INIT Microbial_population = 1E16
DOCUMENT: This population is an estimate for the entire microbial community in the wetland. Units are colony forming units based on 50% cattail and 50% reed plants.

Birth_inflow = Microbial_population*Birth_fraction*(1-Density_factor)
DOCUMENT: This inflow accounts for the births into the microbial population. Units are in colony forming units per day.

Death_outflow = Microbial_population*Death_fraction*Density_factor
DOCUMENT: This outflow represents that fraction of the microbial population which dies each day. Units are colony forming units per day.

Birth_fraction =
(Plant_biomass/300000)*B_pH_conversion*Ratio_conversion_3*Dissolved_Oxygen*Nutrient_availability*B_temp_conversion
DOCUMENT: This factor accounts for all those effects which affect the ability of the microbial population to reproduce and grow. Units are a dimensionless fraction.

Death_fraction = D_pH_conversion*D_temp_conversion*(1.5127-Dissolved_Oxygen)
DOCUMENT: This fraction represents all the effects of the different variables on the death outflow rate. This fraction is an estimate since it combines a variety of factors whose interactions and potential synergisms are not well known. Fraction is dimensionless.

Dissolved_Oxygen = .9
DOCUMENT: This factor accounts for the possible effects of dissolved oxygen values on the microbial population. It is assumed for this particular situation that the dissolved oxygen value is not a limiting condition for the microbial population. That is, there are almost always optimum dissolved oxygen conditions available to the microbial population. This is an estimate since there are both aerobic and anaerobic microbial communities within the wetland and both are very important to its effective operation. Since the microbial population is primarily concerned with plant decomposition and metal return in this model, it is assumed that aerobic processes of plant decay are more important to the overall description of the wetland. Aerobic decay mechanisms tend to be quicker and produce less undesireable products.

pH = 8
DOCUMENT: This variable represents the pH condition in the wetland. It is assumed to remain constant throughout the simulation although this may or may not be a relatively constant value in reality.

Water_temperature = 61
DOCUMENT: This graph depicts the average monthly water temperature for the Atlanta, GA area. The temperature is assumed to be continuous throughout the course of the day, with no temperature variations day to day or throughout each day. The temperature of the wetland water will tend to vary less than the ambient air temperature, thus increasing the survival of the microbial population.

B_pH_conversion = GRAPH(pH)
(0.00, 0.1), (1.00, 0.3), (2.00, 0.5), (3.00, 0.7), (4.00, 0.835), (5.00, 0.92), (6.00, 0.975), (7.00, 1.00), (8.00. 0.975), (9.00, 0.92), (10.0, 0.835), (11.0, 0.7), (12.0, 0.5), (13.0, 0.3), (14.0, 0.1)
DOCUMENT: This graph accounts for the effects of pH on the microbial birth fraction. According to the Hammer text, Portier article, an optimum pH range would be circumneutral, containing values from 6-8. Therefore values within this range will increase the birth fraction, while values outside the range will tend to decrease the birth fraction.

B_temp_conversion = GRAPH(Water_temperature)
(42.0, 0.022), (43.0, 0.025), (44.0, 0.028), (45.0, 0.031), (46.0, 0.034), (47.0, 0.037), (48.0, 0.04), (49.0, 0.043), (50.0, 0.046), (51.0, 0.049), (52.0, 0.052), (53.0, 0.055), (54.0, 0.058), (55.0, 0.061), (56.0, 0.064), (57.0, 0.067), (58.0, 0.07), (59.0, 0.073), (60.0, 0.076), (61.0, 0.079), (62.0, 0.082), (63.0, 0.085), (64.0, 0.088), (65.0, 0.091), (66.0, 0.094), (67.0, 0.097), (68.0, 0.1), (69.0, 0.1), (70.0, 0.1), (71.0, 0.1), (72.0, 0.1), (73.0, 0.1), (74.0, 0.1), (75.0, 0.1), (76.0, 0.1), (77.0, 0.1), (78.0, 0.1), (79.0, 0.1)
DOCUMENT: This conversion takes the temperature value and creates a fraction which represents that temperature's potential effect (compared to optimum) on the microbial population. It is a limiting factor on the birth fraction. Optimum conditions for most microbial populations are in the 20-30 degree Celcius range. However such communities can exist below optimum production efficiency in a wide range of temperatures. Temperature extremes, like pH extremes tend to reduce that less resistant fraction of the microbial population causing less diversity and greater chance for complete microbial exinction.

Density_factor = GRAPH(Microbial_population)
(0.00, 0.005), (2.5e+015, 0.04), (5e+015, 0.07), (7.5e+015, 0.12), (1e+016, 0.155), (1.3e+016, 0.195), (1.5e+016, 0.25), (1.8e+016, 0.325), (2e+016, 0.415), (2.3e+016, 0.54), (2.5e+016, 0.68), (2.8e+016, 0.86), (3e+016, 0.993)
DOCUMENT: This factor accounts for the microbial carrying capacity of the wetland and limits the growth of the microbial population. This graph represents an estimate since carrying capacity is dependent on specific setting and can be highly variable.

D_pH_conversion = GRAPH(pH)
(0.00, 0.9), (1.00, 0.85), (2.00, 0.8), (3.00, 0.75), (4.00, 0.7), (5.00, 0.655), (6.00, 0.62), (7.00, 0.6), (8.00, 0.62), (9.00, 0.655), (10.0, 0.7), (11.0, 0.75), (12.0, 0.8), (13.0, 0.85), (14.0, 0.9)
DOCUMENT: This graph converts the pH value into a factor affecting microbial death fraction. Optimum pH ranges from 6-8, so values outside this range would tend to increase the death fraction, while values in this range will decrease the death fraction.

D_temp_conversion = GRAPH(Water_temperature)
(42.0, 0.1), (43.0, 0.097), (44.0, 0.094), (45.0, 0.091), (46.0, 0.088), (47.0, 0.085), (48.0, 0.082), (49.0, 0.079), (50.0, 0.076), (51.0, 0.073), (52.0, 0.07), (53.0, 0.067), (54.0, 0.064), (55.0, 0.061), (56.0, 0.058), (57.0, 0.055), (58.0, 0.052), (59.0, 0.049), (60.0, 0.046), (61.0, 0.043), (62.0, 0.04), (63.0, 0.037), (64.0, 0.034), (65.0, 0.031), (66.0, 0.028), (67.0, 0.025), (68.0, 0.022), (69.0, 0.019), (70.0, 0.016), (71.0, 0.013), (72.0, 0.01), (73.0, 0.007), (74.0, 0.004), (75.0, 0.002), (76.0, 0.002), (77.0, 0.002), (78.0, 0.002), (79.0, 0.002)
DOCUMENT: This conversion takes the temperature value and creates a fraction which represents that temperature's potential effect (compared to optimum) on the microbial population. It is a limiting factor on the death fraction. Its effect is the reciprical of the birth temperature conversion.

Nutrient_availability = GRAPH(Plant_litter)
(0.00, 0.005), (1667, 0.24), (3333, 0.42), (5000, 0.605), (6667, 0.755), (8333, 0.845), (10000, 0.9), (11667, 0.93), (13333, 0.96), (15000, 0.97), (16667, 0.985), (18333, 0.995), (20000, 1.00)
DOCUMENT: This graph represents the nutrients available to the microbial population by way of plant decay. This value is low at first due to start-up conditions but quickly becomes a non-limiting factor on microbial growth.

Ratio_conversion_3 = GRAPH(Plant_species_ratio)
(1.00, 0.19), (2.00, 0.597), (3.00, 1.00)
DOCUMENT: This conversion changes a selected plant species ratio (percent cattails and reeds in the wetland) to a growth factor affecting the birth inflow for the microbial population. Based on the Hatano article in the Morishi text, cattail plants support only one-fifth the number of microbial colony forming units as do reed cells.

Plant Biomass

Plant_biomass(t) = Plant_biomass(t - dt) + (Plant_growth_rate - Plant_death_rate - Harvest_outflow) * dt
INIT Plant_biomass = 50000
DOCUMENT: This stock represents the accumulation of plant biomass in the wetland. Units are in kg of biomass.

Plant_growth_rate = Plant_biomass*Plant_productivity*(1-Plant_density_factor)
DOCUMENT: This growth rate represents the plant biomass growth rate which is a function of the plant biomass already in the wetland, the plant productivity factor, and the density dependent factors defined by the plant density factor. Units are in kg/day.

Plant_death_rate = Plant_biomass*Death_reduction*Plant_density_factor

DOCUMENT: This death rate represents the reduction of plant biomass which is a function of the plant biomass already in the wetland, the death reduction fraction, and the plant density factor. Units are in kg/day.

Harvest_outflow = Plant_biomass*0
DOCUMENT: This outflow of plant biomass represents the harvesting and disposal of plant biomass outside the wetland boundary. Units are in kg/day.

Plant_litter(t) = Plant_litter(t - dt) + (Plant_death_rate - Plant_decomposition_rate) * dt
INIT Plant_litter = 0
DOCUMENT: This stock represents the accumulation of dead plant biomass in the wetland. Units are in kg of biomass.

Plant_death_rate = Plant_biomass*Death_reduction*Plant_density_factor
DOCUMENT: This death rate represents the reduction of plant biomass which is a function of the plant biomass already in the wetland, the death reduction fraction, and the plant density factor. Units are in kg/day.

Plant_decomposition_rate = Plant_litter*Decomposing_activity
DOCUMENT: This equation defines the rate at which plant litter is returned to the soil. This return includes the return of metals to the soil as well as the nutrients formerly contained in the plant itself. Units are in kg/day.

Air_temperature = 61
DOCUMENT: This graph depicts the average monthly ambient air temperature for the Atlanta, GA area. The temperature is assumed to be continuous throughout the course of the day, with no temperature variations day to day or throughout each day.

Death_reduction = D_temp_conversion_2*Water_level_factor_2
DOCUMENT: This fraction represents all important factors affecting the plant death rate in the wetland. This value is an estimate since the combinations and weights of the individual factors in concert with one another is not well known.

Nutrient_Availability_2 = 1
DOCUMENT: This factor accounts for the nutrients available for plant use at any given time. A factor of one represents a scenario where the plants are not nutrient limited which is the assumed case for this model. Nutrients are assumed to be inherent and adequate in both the water inflows and wetland soil. Reality could dictate otherwise.

Plant_productivity =
Nutrient_Availability_2*B_temp_conversion_2*(Ratio_conversion_2/34.51)*Water_level_factor
DOCUMENT: This factor accounts for all the variables that influence the productivity of the plant biomass in the wetland. This factor is an estimate since the synergies of the incoming factors are not well known.

Plant_species_ratio = 2
DOCUMENT: This ratio denotes the percentages of cattail and reed in the CW. A value of 1 indicates 100% cattail, 2 denotes 50% cattail and 50% reed, and 3 denotes 100% reed.

B_temp_conversion_2 = GRAPH(Air_temperature)
(42.0, 0.22), (43.0, 0.25), (44.0, 0.28), (45.0, 0.31), (46.0, 0.34), (47.0, 0.37), (48.0, 0.4), (49.0, 0.43), (50.0, 0.46), (51.0, 0.49), (52.0, 0.52), (53.0, 0.55), (54.0, 0.58), (55.0, 0.61), (56.0, 0.64), (57.0, 0.67), (58.0, 0.7), (59.0, 0.73), (60.0, 0.76), (61.0, 0.079), (62.0, 0.82), (63.0, 0.85), (64.0, 0.88), (65.0, 0.91), (66.0, 0.94), (67.0, 0.97), (68.0, 1.00), (69.0, 1.00), (70.0, 1.00), (71.0, 1.00), (72.0, 1.00), (73.0, 1.00), (74.0, 1.00), (75.0, 1.00), (76.0, 1.00), (77.0, 1.00), (78.0, 1.00), (79.0, 1.00)
DOCUMENT: This conversion takes the temperature value and creates a fraction which represents that temperature's potential effect (compared to optimum) on the plant productivity. It is a limiting factor on the birth fraction in this case. Optimum conditions are usually seen in early summer and late spring.

Decomposing_activity = GRAPH(Microbial_population)
(0.00, 0.00), (2.1e+015, 0.015), (4.2e+015, 0.05), (6.3e+015, 0.1), (8.4e+015, 0.15), (1.1e+016, 0.203), (1.3e+016, 0.235), (1.5e+016, 0.265), (1.7e+016, 0.278), (1.9e+016, 0.29), (2.1e+016, 0.295), (2.3e+016, 0.3), (2.5e+016, 0.3)
DOCUMENT: This graph represents the ability of the microbial population to degrade and decay the dead plant biomass in the wetland. The greater the population, the greater the ability to cause decomposition and the less time it takes to complete such activity.

D_temp_conversion_2 = GRAPH(Air_temperature)
(42.0, 1.00), (43.0, 0.97), (44.0, 0.94), (45.0, 0.91), (46.0, 0.88), (47.0, 0.85), (48.0, 0.82), (49.0, 0.79), (50.0, 0.76), (51.0, 0.73), (52.0, 0.7), (53.0, 0.67), (54.0, 0.64), (55.0, 0.61), (56.0, 0.58), (57.0, 0.55), (58.0, 0.52), (59.0, 0.49), (60.0, 0.46), (61.0, 0.043), (62.0, 0.4), (63.0, 0.37), (64.0, 0.34), (65.0, 0.31), (66.0, 0.28), (67.0, 0.25), (68.0, 0.22), (69.0, 0.19), (70.0, 0.16), (71.0, 0.13), (72.0, 0.1), (73.0, 0.07), (74.0, 0.04), (75.0, 0.02), (76.0, 0.02), (77.0, 0.02), (78.0, 0.02), (79.0, 0.02)
DOCUMENT: This conversion takes the given temperature and converts it into a factor which accounts for the number of plants that typically die at this value. The value produced is a fraction of the optimum death rate which would be seen at temperature extremes of cold and heat.

Plant_density_factor = GRAPH(Plant_biomass)
(0.00, 0.5), (27083, 0.5), (54167, 0.51), (81250, 0.51), (108333, 0.515), (135417, 0.53), (162500, 0.555), (189583, 0.59), (216667, 0.63), (243750, 0.67), (270833, 0.735), (297917, 0.83), (325000, 1.00)
DOCUMENT: This factor and associated graph limits the amount of plant biomass in the wetland based on a maximum value of 10 kg of biomass per meter squared. This value is an estimate from a number of texts as well as the graph of values that enforces it.

Ratio_conversion_2 = GRAPH(Plant_species_ratio)
(1.00, 34.5), (2.00, 30.5), (3.00, 26.5)
DOCUMENT: This graph represents the possible plant ratios and their respective net primary production rates. Cattail is expected to have a NPP rate of 27.4 mt/ha/yr while reeds are expected to have NPP rates of about 21mt/ha/yr. 50% of cattail and 50% of reed will produce something in between these two extremes. For the purposes of this model these values have been converted to a daily production rate for the wetland using the dimensions of the wetland itself. Units are in kg/day.

Water_level_factor = GRAPH(Actual_water_level)
(-0.15, 0.1), (-0.0893, 0.485), (-0.0286, 0.74), (0.0321, 0.915), (0.0928, 1.00), (0.154, 1.00), (0.214, 1.00), (0.275, 0.93), (0.336, 0.81), (0.396, 0.625), (0.457, 0.4)
DOCUMENT: This graph converts the actual water level (water level above the top of soil mass in the wetland) into a helpful or hindering fraction that accounts for the effect of water level on plant productivity. Since the only plants of importance in this wetland are cattail and reed, optimum water conditions are considered to around 20 cm, which is a typical value for wetland emergent vegetation. Values have been associated with table 4-1 and 4-2 from the State of Maryland document, pages 103-104.

Water_level_factor_2 = GRAPH(Actual_water_level)
(-0.15, 2.50), (-0.0994, 2.03), (-0.0488, 1.66), (0.00175, 1.41), (0.0523, 1.23), (0.103, 1.10), (0.154, 1.00), (0.204, 1.00), (0.255, 1.00), (0.305, 1.13), (0.356, 1.41), (0.406, 2.13), (0.457, 3.50)
DOCUMENT: This graph converts the actual water level (or water level above the top of soil mass in the wetland) into a helpful or hindering fraction that accounts for the effect of water level on the plant death rate. Values are derived from the State of Maryland observations on optimum water levels for species of cattail and reed plants. Water depths greater than 60 cm have tended to eliminate such emergent vegetation from wetlands, while similar responses have been associated with lack of water.

Soil

Soil_in_CW(t) = Soil_in_CW(t - dt) + (Secondary_sedimentation - Soil_resuspension_rate) * dt
INIT Soil_in_CW = 56446470
DOCUMENT: This stock represents the accumulation of additional sediment in the wetland soil. Units are in kg. Starting value represents 1.8 meters of soil at 90 pounds per cubic foot.

Secondary_sedimentation = (Soil_in_CW_water/Secondary_sedimentation_time)*Plant_biomass/210000
DOCUMENT: This flow rate represents the sedimentation rate experienced in the wetland. It is a function of both detention time and plant biomass unlike the primary sedimentation rate realized in the detention pond which was solely dependent on its detention time. Units are in kg/day.

Soil_resuspension_rate = GRAPH(CW_detention_time/Secondary_sedimentation_time)
(0.00, 7600), (0.833, 4300), (1.67, 2000), (2.50, 950), (3.33, 550), (4.17, 350), (5.00, 250), (5.83, 200), (6.67, 150), (7.50, 100), (8.33, 50.0), (9.17, 50.0), (10.0, 10.0)
DOCUMENT: This graph represents the rate at which sediment from the wetland soil stock will be resuspended into the wetland water stock. This rate is based solely on the detention time in the wetland. Long detention times equate to low resuspension rates, however short detention times correspond to large resuspension rates. Once a particle is resuspended, it still has a chance of sedimenting out of solution again. however it can also flow out of the wetland at this point also. Units are in kg/day.

Soil_in_CW_water(t) = Soil_in_CW_water(t - dt) + (Soil_resuspension_rate + CW_soil_inflow_rate - Secondary_sedimentation - Soil_loss_rate) * dt
INIT Soil_in_CW_water = 0
DOCUMENT: This stock represents the accumulation of soil in the wetland water volume. Units are in kg.

Soil_resuspension_rate = GRAPH(CW_detention_time/Secondary_sedimentation_time)
(0.00, 7600), (0.833, 4300), (1.67, 2000), (2.50, 950), (3.33, 550), (4.17, 350), (5.00, 250), (5.83, 200), (6.67, 150), (7.50, 100), (8.33, 50.0), (9.17, 50.0), (10.0, 10.0)

DOCUMENT: This graph represents the rate at which sediment from the wetland soil stock will be resuspended into the wetland water stock. This rate is based solely on the detention time in the wetland. Long detention times equate to low resuspension rates, however short detention times correspond to large resuspension rates. Once a particle is resuspended, it still has a chance of sedimenting out of solution again, however it can also flow out of the wetland at this point also. Units are in kg/day.

CW_soil_inflow_rate = CW_inflow*(Soil_conc_in_DP_water*1000)
DOCUMENT: This equation represents the fraction of suspended sediment that leaves the detention pond without falling out of solution. This flow is characterized by both the fraction that was settleable but did not settle and the fraction that was not settleable in the first place. Units are in kg/day.

Secondary_sedimentation = (Soil_in_CW_water/Secondary_sedimentation_time)*Plant_biomass/210000
DOCUMENT: This flow rate represents the sedimentation rate experienced in the wetland. It is a function of both detention time and plant biomass unlike the primary sedimentation rate realized in the detention pond which was solely dependent on its detention time. Units are in kg/day.

Soil_loss_rate = CW_outflow*Soil_conc_in_CW_water
DOCUMENT: This equation describes the rate at which sediment suspended in the wetland water will flow out of the wetland. This co-flow process is an estimate and may not be truly representative of the actual wetland process since suspended particles leaving the wetland via this path may not have yet been acted upon by the wetland sedimentation processes. Units are in kg/day.

Soil_in_DP_sediment(t) = Soil_in_DP_sediment(t - dt) + (Primary_sedimentation - Sediment_removal) * dt
INIT Soil_in_DP_sediment = 1
DOCUMENT: This stock represents the accumulation of soil/sediment on the floor of the detention basin. Units are in kg.

Primary_sedimentation = Soil_in_DP_water/Primary_sedimentation_time
DOCUMENT: This equation represents the rate at which particulate matter and suspended sediments in the detention pond water fall out of solution and become part of the sediment on the basin's floor. Units are given in kg/day.

Sediment_removal = Sediment_removal_fraction*Soil_in_DP_sediment
DOCUMENT: This equation represents the rate at which sediment is removed from the floor of the detention pond. Removal of sediment is assumed to take place when the maximum amount of sediment is reached. This value and corresponding removal rate would be solely a managerial decision based on expected detention pond efficiency. Units are in kg/day.

Soil_in_DP_water(t) = Soil_in_DP_water(t - dt) + (DP_soil_inflow_rate - Primary_sedimentation - CW_soil_inflow_rate) * dt
INIT Soil_in_DP_water = 0
DOCUMENT: This stock represents the accumulation of soil/sediment in the detention pond water. Units are in kg.

DP_soil_inflow_rate = Storm_water_rate*Soil_conc_in_DP_inflow

DOCUMENT: This equation represents the rate at which suspended sediments flow into the detention pond water volume. Units are in kg/day.

Primary_sedimentation = Soil_in_DP_water/Primary_sedimentation_time
DOCUMENT: This equation represents the rate at which particulate matter and suspended sediments in the detention pond water fall out of solution and become part of the sediment on the basin's floor. Units are given in kg/day.

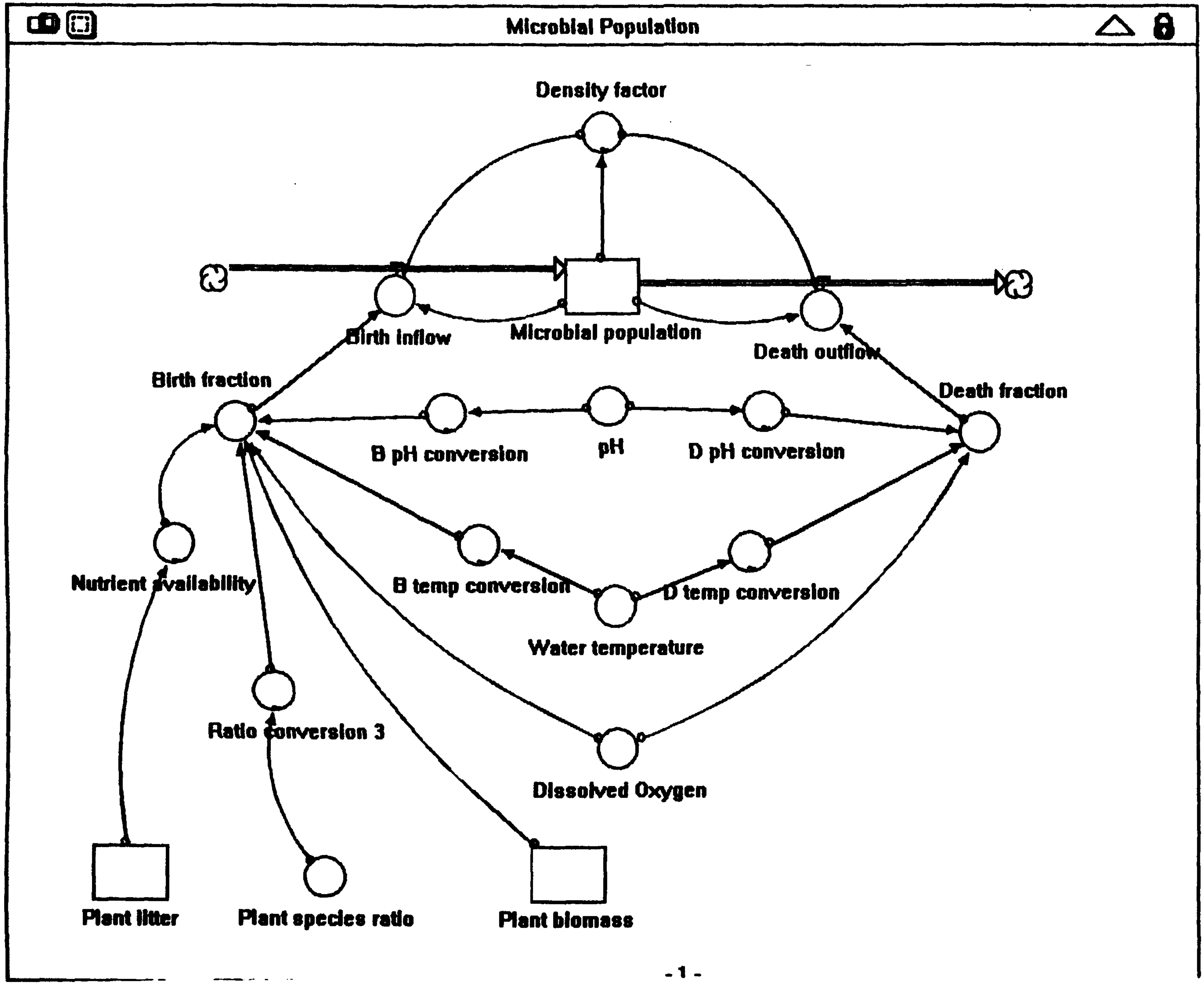
CW_soil_inflow_rate = CW_inflow*(Soil_conc_in_DP_water*1000)
DOCUMENT: This equation represents the fraction of suspended sediment that leaves the detention pond without falling out of solution. This flow is characterized by both the fraction that was settleable but did not settle and the fraction that was not settleable in the first place. Units are in kg/day.

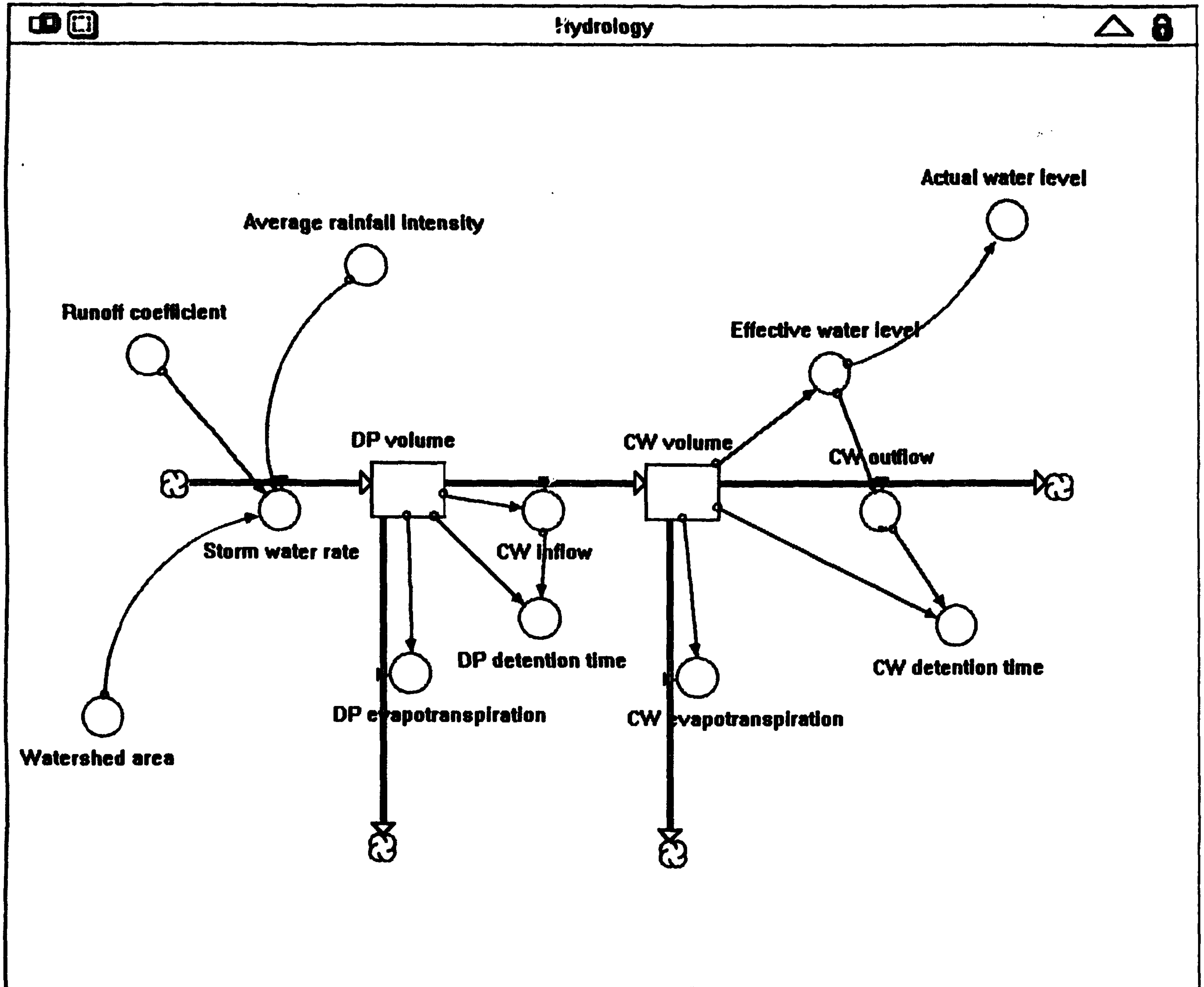
Max_sediment_volume = 1098665
DOCUMENT: This value equals approximately one foot of sediment in the sedimentation basin.

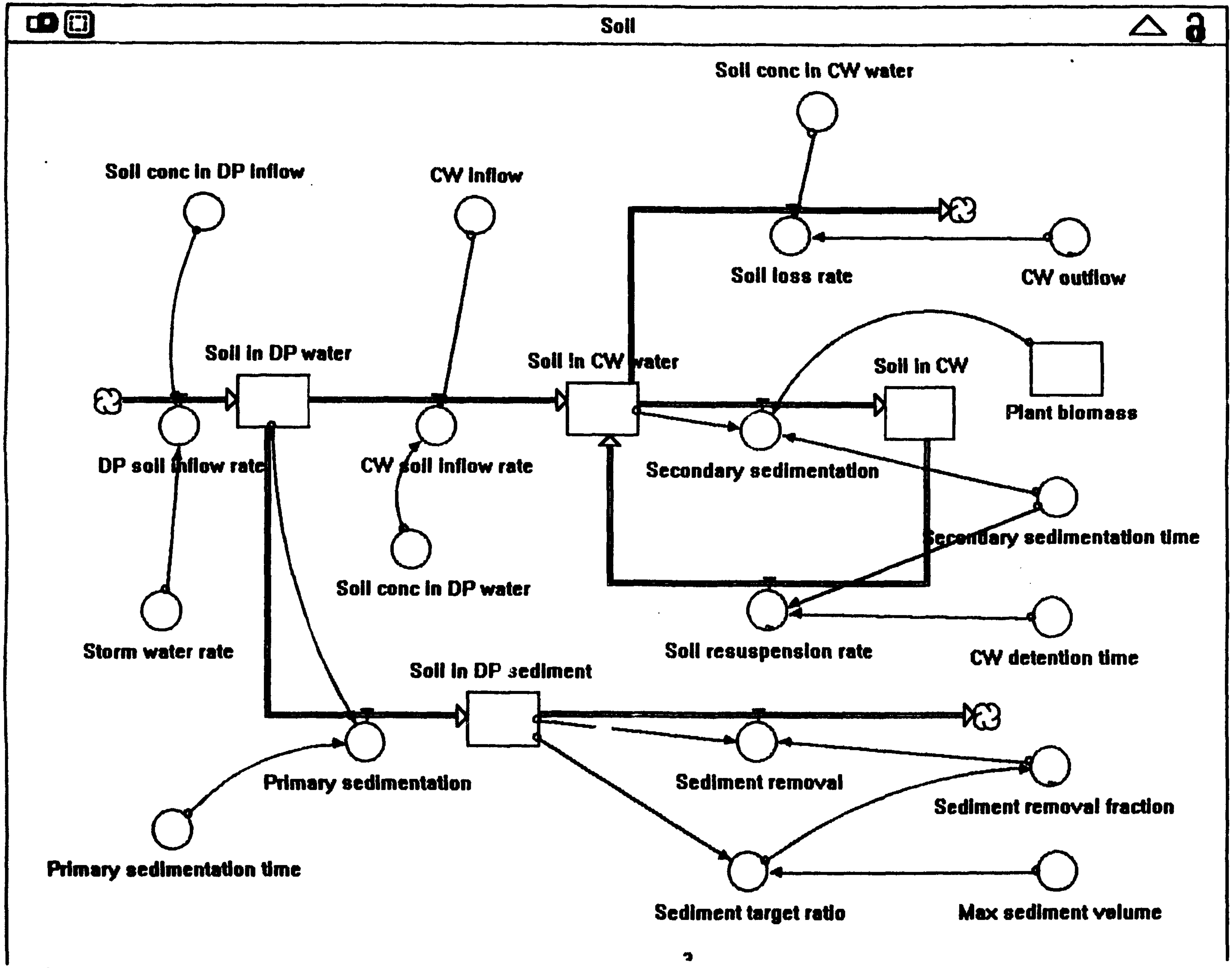
Primary_sedimentation_time = 18/24
Secondary_sedimentation_time = 5
Sediment_target_ratio = Soil_in_DP_sediment/Max_sediment_volume
DOCUMENT: This ratio represents how close to the removal goal the actual amount of sediment in the detention pond really is. Once this ratio becomes close enough to 1, action will be taken to remove the accumulated sediment.

Soil_conc_in_DP_inflow = 71.07
DOCUMENT: This equation produces a range of values that depict the TSS average values for AF storm water runoff. Values are in mg/l.

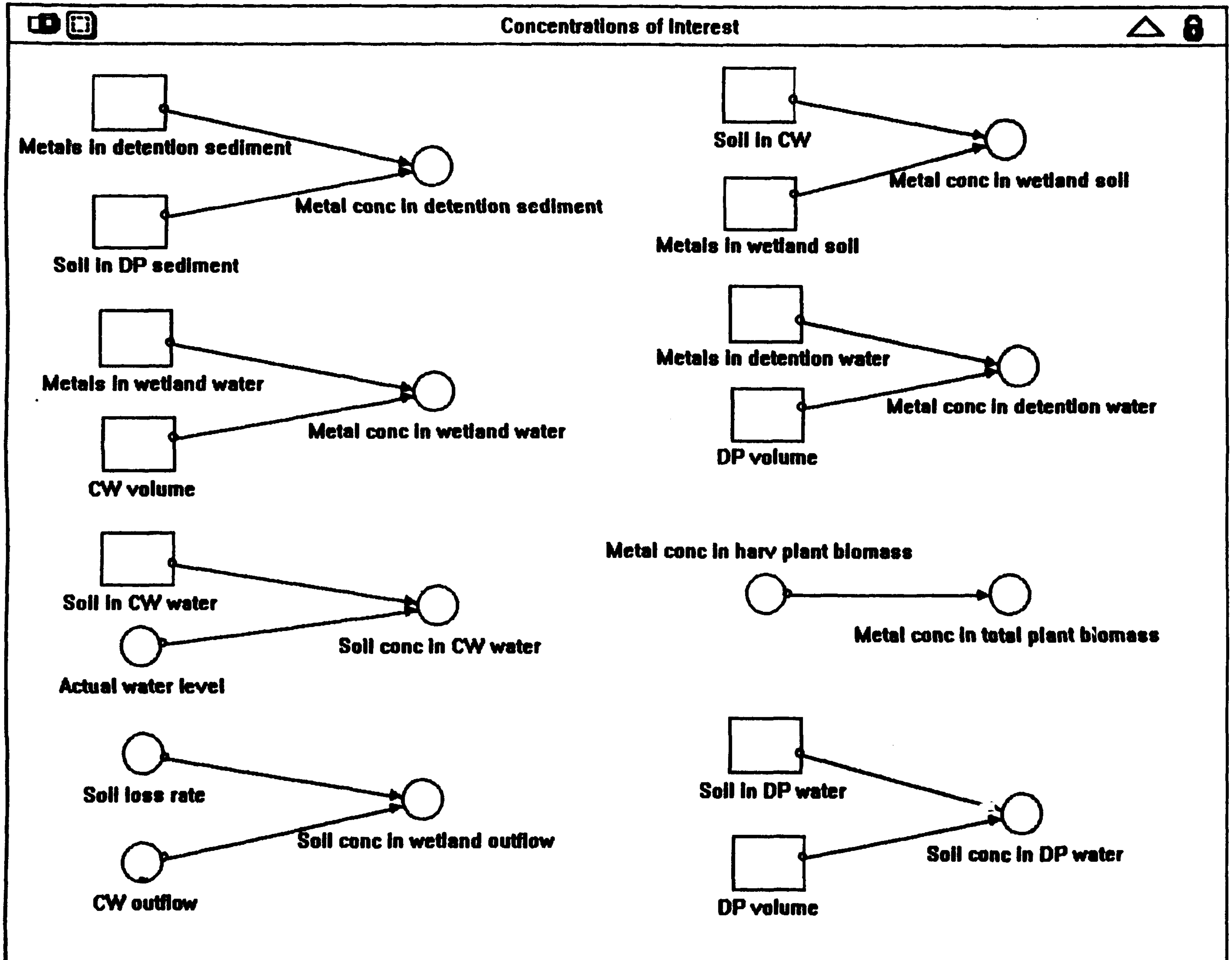
Sediment_removal_fraction = GRAPH(Sediment_target_ratio)
(0.00, 0.00), (0.125, 0.00), (0.25, 0.00), (0.375, 0.00), (0.5, 0.67), (0.625, 1.17), (0.75, 1.54), (0.875, 1.74), (1.00, 1.83), (1.13, 1.88), (1.25, 1.91), (1.38, 1.93), (1.50, 1.93)
DOCUMENT: This graph represents the fraction of sediment removal based on the target ratio. As the target ratio gets close to one, sediment removal will take place to reduce the volume of sediment in the detention pond.

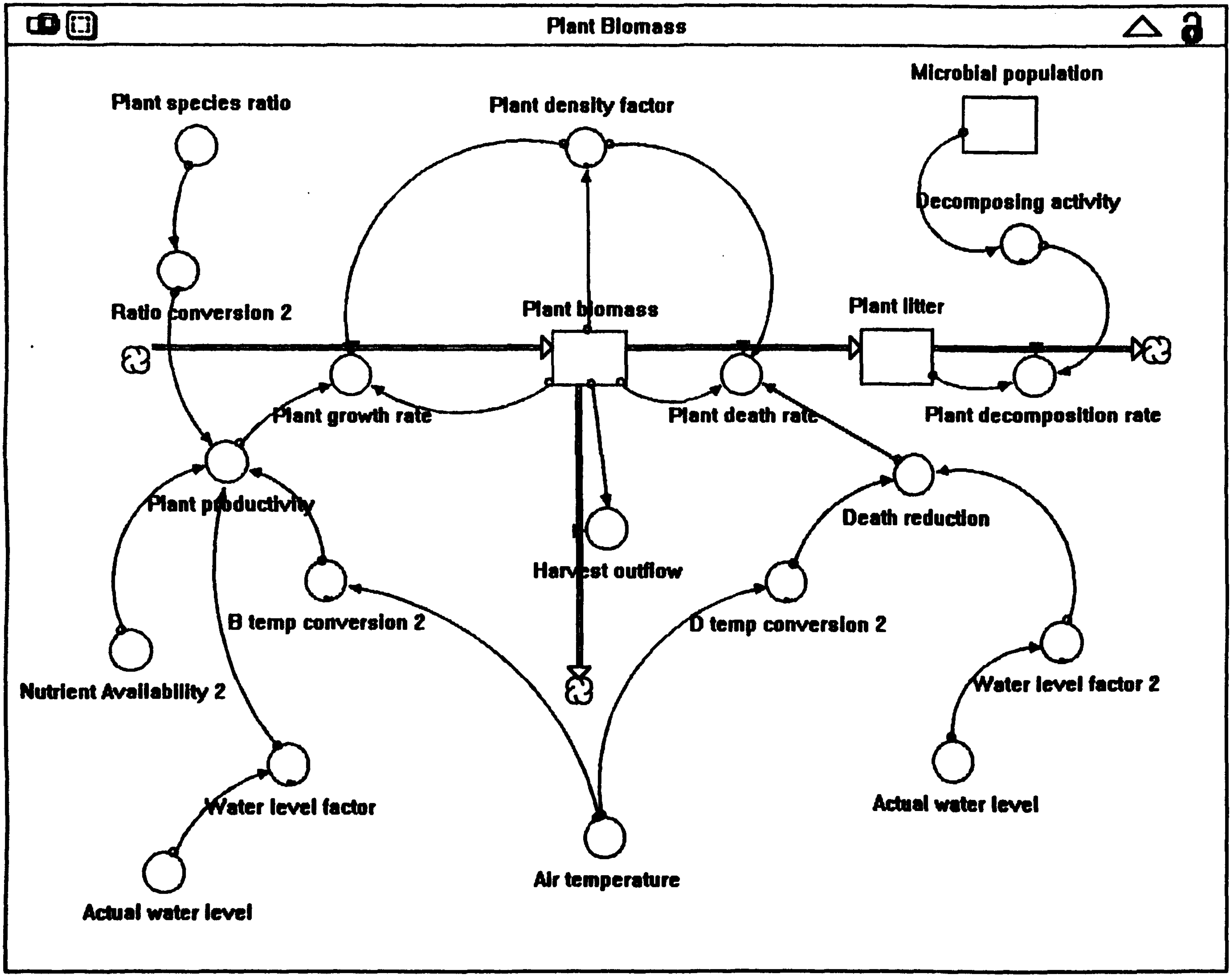

Microbial Population
Density factor
Birth inflow
Microbial population
Death outflow
Birth fraction
Death fraction
B pH conversion
pH
D pH conversion
Nutrient availability
B temp conversion
D temp conversion
Water temperature
Ratio conversion 3
Dissolved Oxygen
Plant litter
Plant species ratio
Plant biomass
- 1 -

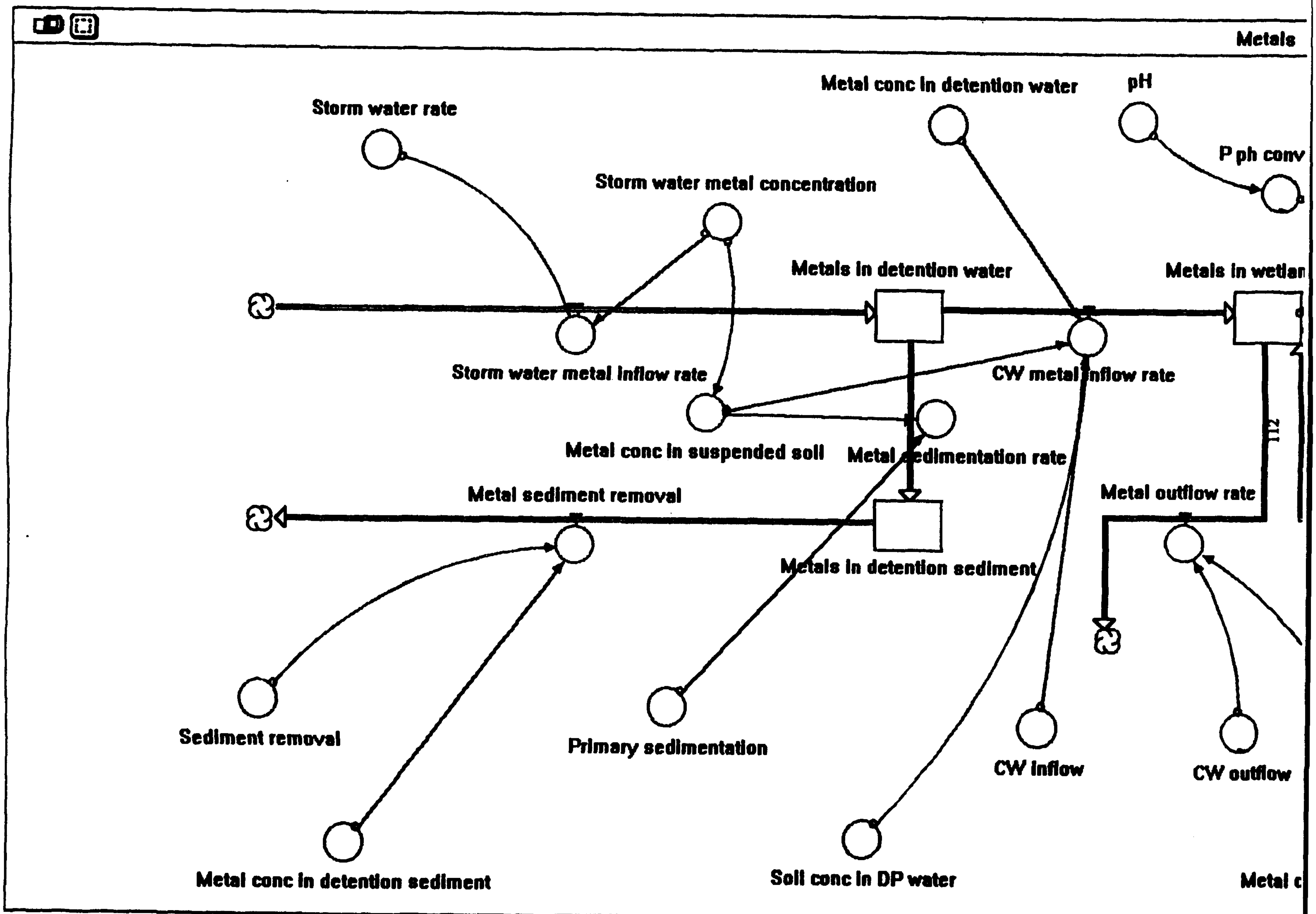

Hydrology
Average rainfall intensity
Runoff coefficient
Actual water level
Effective water level
DP volume
CW volume
CW outflow
Storm water rate
CW inflow
DP detention time
CW detention time
DP evapotranspiration
CW evapotranspiration
Watershed area

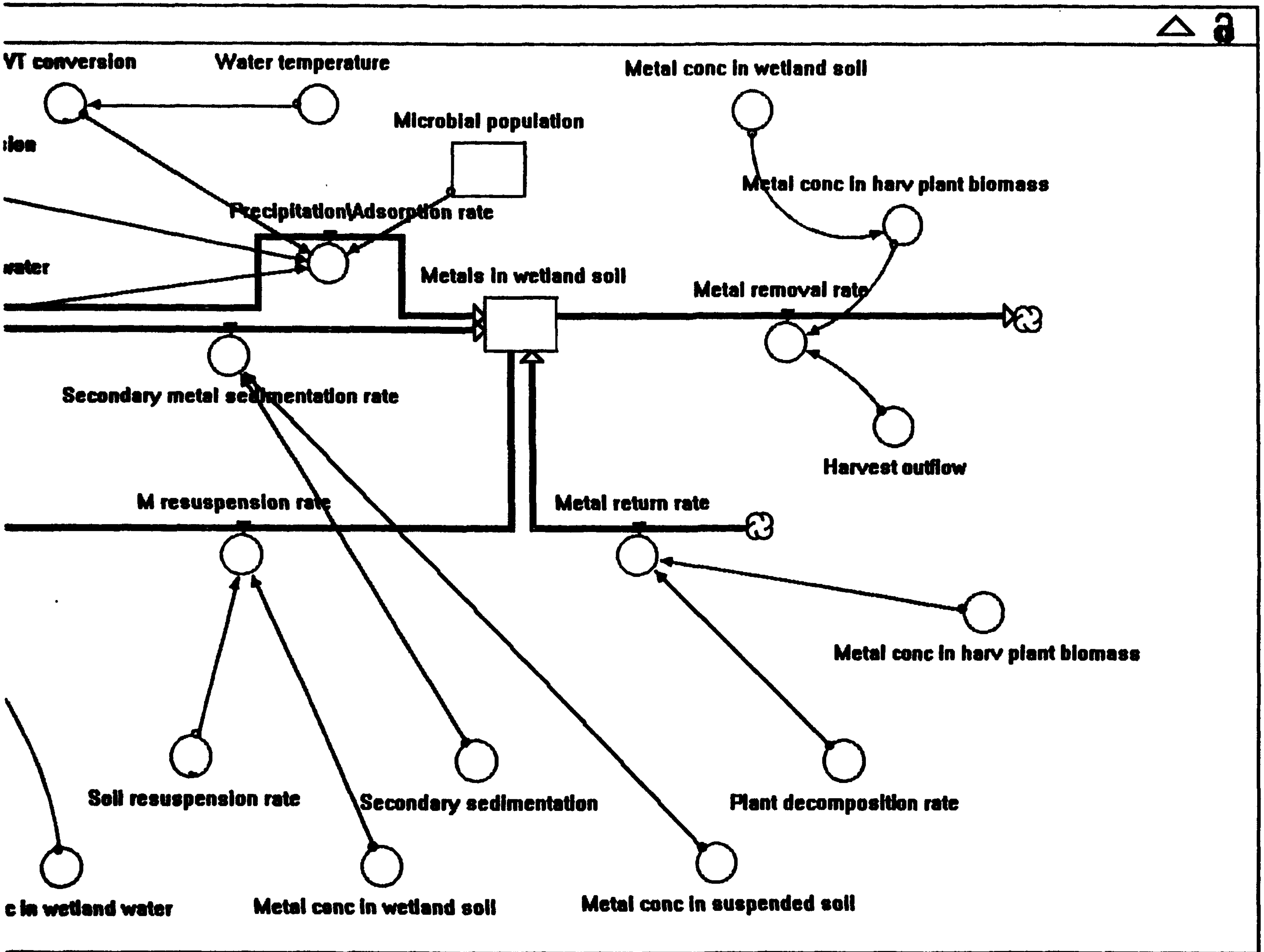


Soil
Soil conc in CW water
Soil conc in DP inflow
CW inflow
Soil loss rate
CW outflow
Soil in DP water
Soil in CW water
Soil in CW
Plant biomass
DP soil inflow rate
CW soil inflow rate
Secondary sedimentation
Secondary sedimentation time
Soil conc in DP water
Storm water rate
Soil resuspension rate
CW detention time
Soil in DP sediment
Primary sedimentation
Sediment removal
Sediment removal fraction
Primary sedimentation time
Sediment target ratio
Max sediment volume


Concentrations of Interest
Metals in detention sediment
Soil in DP sediment
Metal conc in detention sediment
Metals in wetland water
CW volume
Metal conc in wetland water
Soil in CW water
Actual water level
Soil conc in CW water
Soil loss rate
CW outflow
Soil conc in wetland outflow
Soil in CW
Metals in wetland soil
Metal conc in wetland soil
Metals in detention water
DP volume
Metal conc in detention water
Metal conc in harv plant biomass
Metal conc in total plant biomass
Soil in DP water
DP volume
Soil conc in DP water


Plant Biomass
Microbial population
Plant species ratio
Plant density factor
Decomposing activity
Ratio conversion 2
Plant biomass
Plant litter
Plant growth rate
Plant death rate
Plant decomposition rate
Plant productivity
Death reduction
Harvest outflow
B temp conversion 2
D temp conversion 2
Nutrient Availability 2
Water level factor 2
Water level factor
Actual water level
Air temperature
Actual water level


Metals
Storm water rate
Storm water metal concentration
Metal conc in detention water
pH
P ph conv
Metals in detention water
Metals in wetlan
Storm water metal inflow rate
CW metal inflow rate
Metal conc in suspended soil
Metal sedimentation rate
112
Metal sediment removal
Metal outflow rate
Metals in detention sediment
Sediment removal
Primary sedimentation
CW inflow
CW outflow
Metal conc in detention sediment
Soil conc in DP water
Metal c



VT conversion
Water temperature
Metal conc in wetland soil
Microbial population
Metal conc in harv plant biomass
Precipitation\Adsorption rate
water
Metals in wetland soil
Metal removal rate
Secondary metal sedimentation rate
Harvest outflow
M resuspension rate
Metal return rate
Metal conc in harv plant biomass
Soil resuspension rate
Secondary sedimentation
Plant decomposition rate
c in wetland water
Metal conc in wetland soil
Metal conc in suspended soil

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Appendix C. Computed Settling Velocities In Still Water

Particle Classification	Particle Diameter (μ)	Particle Settling Velocity (mm/s)
Sand		
Very Coarse	1000 - 2000	100 -200
Coarse	500 - 1000	53 - 100
Medium	250 - 500	26 - 53
Fine	125 - 250	11 - 26
Very Fine	62 - 125	2.6 - 11
Silt		
Coarse	31 - 62	0.660 - 2.6
Medium	16 - 31	0.180 - 0.66
Fine	8 - 16	0.044 - 0.180
Very Fine	4 - 8	0.011 - 0.044
Clay	< 4	< 0.011

State of Maryland Sediment and Stormwater Division, page 44.

Appendix D. Glossary

Adsorption: The ability to attract and concentrate upon surfaces molecules of gases, liquids, and dissolved solids; the adhesion of molecules to the surfaces or liquids with which they are in contact. Many pollutants adsorb to sediment particles and are transported by these particles.

Best Management Practices (BMP's): A method, activity, maintenance procedure, or other management practice for reducing the amount of pollution entering a water body. BMP's generally fall into two categories: source control BMP's and storm water treatment BMP's. The term originated from the rules and regulations developed pursuant to section 208 of the federal Clean Water Act (40 CFR 130).

Bioaccumulation: The process by which a contaminant accumulates in the tissues of an individual organism. For example, certain chemicals in food eaten by a fish tend to accumulate in its liver and other tissues.

Biochemical oxygen demand (BOD): An index of the quantity of oxygen-demanding substances (organic matter subject to bacterial decay) in a sample as measured by a specific test. Although not a specific compound, BOD is defined as a conventional pollutant under the federal Clean Water Act. During bacterial decay and digestion processes, oxygen is used, reducing dissolved oxygen levels in the water column. Sources of BOD which have the capacity for causing abnormally low dissolved oxygen levels include sewage treatment and septic tank effluents, oil and grease, pesticides, organics of natural origins, and any other decomposable material. Sewage effluent from secondary treatment have a BOD level of 30 mg/l. Urban runoff can have a BOD level equal to or greater than sewage effluents.

Cattail: A perennial, rhizomatous herb with long, sword-like leaves arising from the base of the plant belonging to the genus Typha. The leaves appear in the spring before the stems. Typha latifolia grows to a height of 1-3 m, with leaf blades flat and 1-2 cm wide. Cattails are very common and aggressive, often forming large, monospecific colonies.

Channel flow: Observable movement of surface water (due to gradient currents) in a confined, concentrated zone. Includes intermittent channels.

Chemical oxygen demand (COD): A measure of the amount of oxygen required to oxidize (with a strong chemical oxidant) organic and oxidizable inorganic compounds in water. Both BOD and COD are two different tests that provide relative measures of demand on oxygen resources.

Constructed wetland: A wetland intentionally created from a non-wetland site for the sole purpose of wastewater of storm water treatment. These wetlands are not normally considered Waters of the United States of Waters of the State.

Contaminant: A substance that is not naturally present in the environment or is present in amounts that can, in sufficient concentration, adversely affect the environment. A contaminant is such concentrations becomes a pollutant.

Conventional contaminant: Convention contaminants as specified under the Clean Water Act are: suspended solids, coliform bacteria, biochemical oxygen demand, pH, and oil and grease. Today a large number of toxic contaminants are of concern in addition to the conventional contaminants.

Created wetland: A wetland intentionally created from a non-wetland site to produce or replace natural habitat (e.g., a compensatory mitigation project). These wetlands are normally considered Waters of the United States or Waters of the State.

Detention: The temporary holding of storm water from a site, with release at a slower rate than it is collected by a drainage facility system.

Detritus: A partially decomposed organic material produced by the disintegration and decay of plant tissues, primarily leaves and stems.

Dissolved oxygen (DO): A measure of the amount of oxygen available for biochemical activity in a given amount of water. Adequate levels of DO are needed to support aquatic life.

Effluent: Solid, liquid, or gaseous wastes that enter the environment as a by-product of human-oriented processes. Also refers to the discharge or outflow of water from ground or subsurface storage.

Emergent vegetation: Dominated by erect, rooted, herbaceous angiosperms which may be temporarily or permanently flooded at the base but do not tolerate inundation of the entire plant. Or if tolerant, plant does not flower when submerged (e.g., bullrushes, cord grasses).

Erosion: The wearing away of land surface by wind or water. Erosion occurs naturally from weather or runoff but can be intensified by land clearing practices.

First flush: Phenomenon observed after a prolonged dry spell in which the concentration of pollutants in runoff is higher in the earlier stages of a storm event.

Functions and values: Wetlands are important because they provide many intrinsic ecological functions (water quality maintenance, fish & wildlife habitat, etc.) and socioeconomic values (flood and erosion control, ground water recharge and water supply, recreation, education, research, food production, etc.). "Functions" generally refer to the ecological (physical, chemical, and biological) processed or attributes of a wetland without regard for their importance to society. "Values" refer to wetland processes or attributes that are valuable or beneficial to society.

Ground water discharge: The movement (usually laterally or upward) of ground water into surface water (e.g., springs).

Ground water recharge: The movement (usually downward) of surface water or precipitation into the ground water flow system.

Heavy metals: Metallic elements, such as mercury, lead, nickel, zinc, and cadmium, that are of environmental concern because they do not degrade over time. Although many are necessary nutrients, they are sometimes magnified in the food chain, and they can be toxic to life in high enough concentrations.

Hydrology: The properties, distribution and circulation of water. Wetland hydrology is the total of all wetness characteristics in areas that are inundated for a sufficient duration to support hydrophytic vegetation.

Macrophytes: Plants large enough to be distinguished without aid of a microscope; macroscopic plants.

Marsh: A common term applied to describe treeless wetlands characterized by shallow water and abundant emergent, floating, and submergent wetland flora. Typically found in shallow basins, on lake margins, along flow gradient rivers, and in low energy tidal areas. Waters may be fresh, brackish, of saline.

Metals: Metals are elements found in rocks and minerals that are naturally released to the environment by erosion, as well as generated by human activities. Certain metals, such as mercury, nickel, zinc, and cadmium, are environmental concern because they are released to the environment in excessive amounts by human activity. They are generally toxic to life at certain concentrations. Since metals are elements, they do not break down in the environment over time and can be incorporated into plant and animal tissue.

Mitigation: The term "mitigation" encompasses a broad array of activities when applied to wetlands management. It describes the efforts to lessen, or compensate for the impacts of a development project. The process of mitigation follows a preferred sequence of options, as defined by the National Environmental Policy Act (NEPA) of 1969:

a. Avoiding the impact altogether by not taking a certain action or parts of an action;

b. Minimizing impacts by limiting the degree or magnitude of the action and its implementation;

c. Rectifying the impact by repairing, rehabilitating, or restoring the affected environment;

d. Reducing or eliminating the impact over time by preservation and maintenance operations during the life of the activity; and

e. Compensating for the impact by replacing or providing substitute resources or environments.

The principle of mitigation is implemented in such a way as to prevent any net losses of wetland functions and values.

Non-point sources (NPS): Typically defined as pollution that is not discharged through pipes but rather originates from a multitude of sources over a large area. They can be divided into source activities related to either land or water use. This is distinguished from point-source pollution. Common sources of non-point pollution include failing septic systems, improper animal-keeping practices, forest practices, and urban and rural runoff.

National Pollutant Discharge Elimination System (NPDES): The EPA's program to control the discharge of pollutants to water of the United States (40 CFR 122.2).

Nutrients: A group of inorganic elements necessary for plant and animal cell growth. Excessive amounts can lead to degradation of water quality, algae blooms, and/or toxicity to certain species. The principal nutrients of concern with respect to water quality are nitrogen and phosphorus. These and other nutrients are essential for the growth of plants and phytoplankton. In excess, however, they can be responsible for undesirable phytoplankton (algae) blooms and the culturally enhanced eutrophication of lakes and estuaries. In freshwater systems nitrogen is usually limiting. The sources of nutrients in urban runoff include lawn and garden fertilizers, pet animal wastes, eroded soil, general organic debris, petroleum fuels, and atmospheric fallout.

pH: A measure of the alkalinity or acidity of a substance which is conducted by measuring the concentration of hydrogen ions in the substance. pH is measured on a scale from 1 to 14, with 1 indicating the most acidic, 7 indication neutral, and 14 the most basic or alkaline. The pH of water influences many of the types of chemical reactions that will occur in it.

Point source: A source of pollutants from a single point of conveyance such as a pipe. For example, the discharge pipe from a sewage treatment plant or a factory is a point source. See non-point source for comparison.

Pollutant: A contaminant in a concentration or amount that adversely alters the physical, chemical, or biological properties of the environment. The term includes pathogens, toxic metals, carcinogens, oxygen-demanding materials, and all other harmful substances. With reference to non point sources, the term is sometimes used to apply to contaminants released in low concentrations from many activities which collectively degrade water quality. As defined in the federal Clean Water Act, pollutant means dredged spoil, solid waste, incinerator residue, sewage, garbage, sewage sludge, munitions, chemical wastes biological materials, radioactive materials, heat, wrecked or discarded equipment, rock, sand, cellar dirt, and industrial, municipal, and agricultural waste discharged into water.

Pretreatment: The treatment of wastewater to remove contaminants prior to discharge into a municipal sewage system, or the treatment of storm water (such as in a grassy swale or sediment trap) prior to discharge downstream.

Primary Treatment: A basic wastewater treatment method that uses settling, skimming, and (usually) chlorination to remove solids, floating materials, and pathogens from wastewater. Primary treatment typically removes about 35 percent of BOD and less than half of the metals and toxic organic substances.

Priority pollutants: Substances listed by EPA under the federal Clean Water Act as toxic and having priority for regulatory controls. The list includes metals (13), inorganic compounds (two), and a broad range of both natural and artificial organic compounds(111). The list of priority pollutants includes some substances which are not of immediate concern in Puget Sound, and it does not include all known harmful compounds.

Reed: Members of the grass family of the genus <u>Phragmites</u>. A very tall grass with a feathery plume.

Retention/detention (R/D) facility: A type of drainage facility designed either (1) to hold runoff for a considerable length of time and then release it by evaporation, plant transpiration, and /or infiltration into the ground; or (2) to hold runoff for a short period of time and then release it to the surface and storm water system. Most facilities do both to some degree.

Retention time: The ratio of wetland volume/average outflow rate (approximately) unless the soil infiltration rate is relatively high.

Rhizome: A creeping underground stem.

Runoff: That portion of the precipitation on a drainage area that is discharged overland from the area to stream channels or drainage systems.

Secondary treatment: A wastewater treatment method that usually involves the addition of biological treatment to the settling, skimming, and disinfection provided by primary treatment. Secondary treatment may remove up to 90 percent of BOD and significantly more metals and toxic organics than primary treatment.

Sector: A part of a model containing all flow rates, variables, and compartments where a particular material (such as water or metal) is accounted for and described. All flows and accumulations within a sector deal exclusively with one specific material however each sector may in turn be influenced by other model sectors.

Sediment: Fragmented material that originates from weathering and erosion of rocks or unconsolidated deposits, and is transported by suspended in, or deposited by water. Certain contaminants tend to collect on and adhere to sediment particles.

Sedimentation: The action or process of depositing particles of waterborne or windborne soil, rock, or other materials; the depositing or formation of sediment.

Sheet flow: Water, usually storm water runoff, flowing in a thin even layer over a relatively wide ground surface, and is not concentrated in discernible channels.

Short-circuiting: The passage of runoff through a buffer strip, wetland, or detention pond, in less than the design treatment time, thereby preventing treatment from occurring.

Storm water: Rainfall which does not infiltrate the ground or evaporate because of impervious land surfaces but which flows onto adjacent land or water courses or is routed into drain/sewer systems.

Suspended solids: Organic or inorganic particles that are suspended in and carried by the water. The term includes sand, mud, and clay particles as well as solids in wastewater. High levels of suspended solids can clog the breathing gills of some fish and suffocate them. When suspended solids settle to stream and lake bottoms, they can clog salmon spawning gravels, suffocating salmon eggs and/or preventing future spawning. Clay and silt sediment particles generally carry other pollutants adsorbed to their surface, including petroleum hydrocarbons, refractory organics, pesticides, and heavy metals.

Wastewater: Effluent from a sewage treatment plant.

Watershed: The geographic region within which water drains into a particular river, stream, or body of water. A watershed includes hills, lowlands, and the body of water into which the land drains. Watershed boundaries are defined by the ridges separating watersheds. Every activity on the surface of the land within a watershed can send pollutants into the water.

Wetlands: Lands transitional between terrestrial and aquatic systems that have water table usually at or near the surface or a shallow covering of water, hydric soils, and a prevalence of hydrophytic vegetation. Note that there are several versions of this definition.

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Vita

Captain Mark Perry Smekrud was born on 2 June 1966 in Wisconsin Rapids, Wisconsin. He graduated from Lincoln High School in Wisconsin Rapids, Wisconsin in 1984. He then attended the United States Air Force Academy in Colorado Springs, Colorado where he graduated in 1988 with a Bachelor of Science in Civil Engineering. Upon graduation, he received a commission in the U.S. Air Force as a regular officer. His first tour of duty was in the 5th Civil Engineering Squadron at Minot AFB, North Dakota. During his four and half year tour at Minot, he held the positions of Design Engineer and Environmental Coordinator. He was selected to attend the School of Engineering, Air Force Institute of Technology, in December of 1993. Upon graduation, he will be assigned to the 375th Civil Engineering Squadron, Scott AFB, Illinois. Captain Smekrud will marry his fiancée, Amy Woitas, on 8 October 1994.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1994

3. REPORT TYPE AND DATES COVERED
Master's Thesis

4. TITLE AND SUBTITLE
A PRELIMINARY SYSTEM DYNAMICS MODEL OF A CONSTRUCTED WETLAND FOR THE MITIGATION OF METALS IN USAF STORM WATER

5. FUNDING NUMBERS

6. AUTHOR(S)

Mark P. Smekrud, Captain, USAF

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Institute of Technology, WPAFB OH. 45433-6583

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/GEE/ENV/94S-24

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This thesis determines the potential removal and corresponding accumulation of trace metals from Air Force storm water in a constructed wetland through the use of a System Dynamics model. The goal is to determine whether constructed wetlands used as storm water best management practices provide efficient metal removal while creating only benign accumulations of such pollutants. Its purpose is to allow Base Civil Engineers a better tool to assess the long-term effects of a constructed wetland used as a storm water mitigation technique. The research is limited to the assessment of typical metal concentrations found in Air Force storm water and a hypothetical constructed wetland system. The thesis uses reviews of present literature to examine the sediment and metal removal processes found in constructed wetlands as well as the hydrologic and biologic functions which affect these processes. Constant storm water flows and concentrations typical of Air Force runoff are used to evaluate the metal mitigation potential of such best management practices. The recommendation resulting from this research is that the Air Force should be able to consider constructed wetlands as a viable best management practice to mitigate metals in storm water. The Air Force's long-term use of properly designed constructed wetlands as storm water best management practices should not prove to accumulate metal concentrations of regulatory concern.

14. SUBJECT TERMS

Constructed Wetland, Storm Water, Metals, Modeling

15. NUMBER OF PAGES
140

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

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